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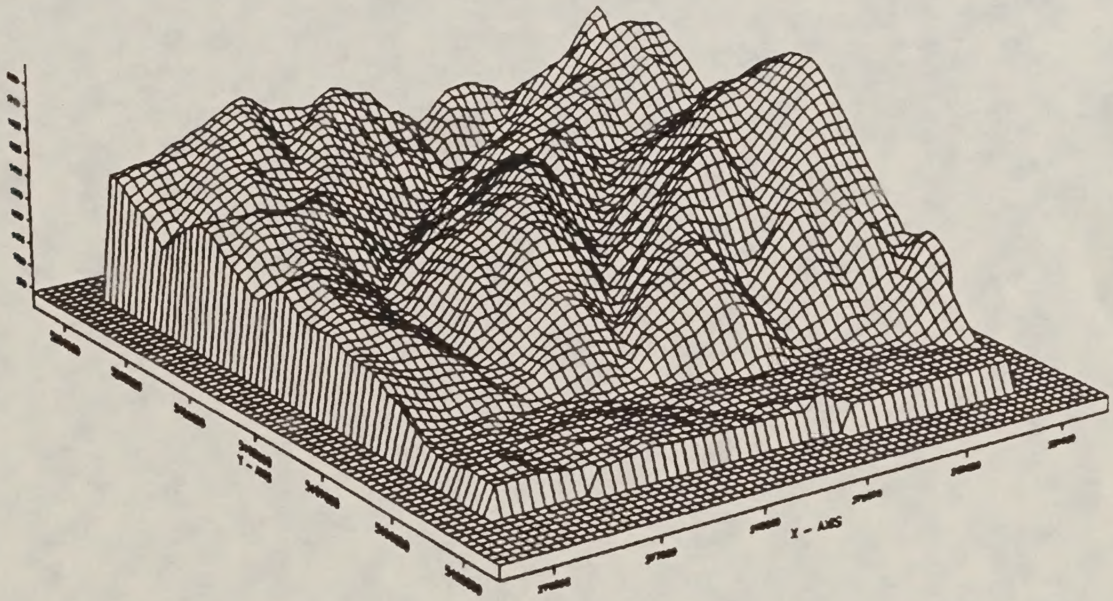
Selection and Verification of Complex Terrain, Wind Flow Model for Spray Transport

Briefing Paper & Progress Report



The cover illustration is a three dimensional plot of Marshall Canyon near Missoula, MT. The flat area in the foreground is a portion of the Missoula Valley. The plot was generated on the Northern Region Data General computer after preprocessing at the Fort Collins Computer Center. The database is available at 30 meter intervals and the GTMS (General Terrain Maniputation System) was used to develop the plots.

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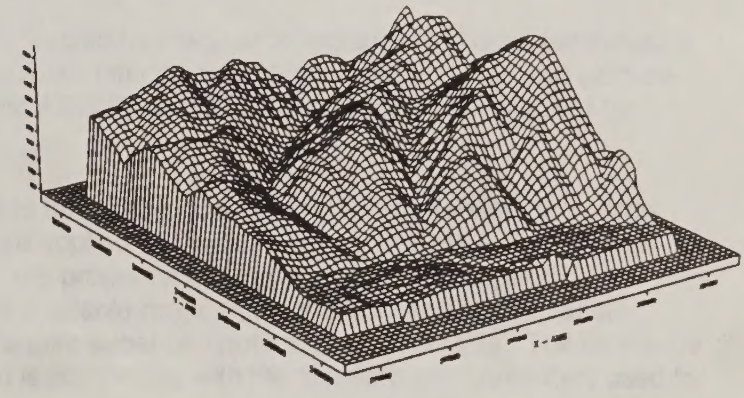

Prepared by
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Program Leader

Technology & Development Program
Missoula, Montana 59801

5E52P29
WIND
July 1990

Objective

To select an existing complex terrain-wind flow model and incorporate it into the AGDISP and FSCBG aerial spray models.

Background

Wind movements near the earth surface are channeled and directed by irregular topographic features, temperature structures, strength of overlying winds, etc. These winds and their intensities determine the direction and ultimate fate of off-site spray movement and where it will deposit. The ADGISP and FSCBG models do not account for irregular topographic features.

Models to describe wind movement over complex terrain have been developed by the Forest Service, U.S. Army, EPA, and others for specialized applications. The models are applied by meteorology specialists and are not accessible for routine use by spray specialists. The models are programmed on computers and depend on the existence of digital terrain descriptions. The models that are available range from simple site specific regulatory models to sophisticated full physics numerical models that require super computers, such as a Cray. The challenge is to select a model that is accurate enough to be useful and is compatible with the software and computers used for our current aerial spray models.

Team Members

John W. Barry	National Aerial Application Specialist. WO FPM, Davis, Calif.	***Dr. Robert Meroney***	Professor. Fluid Mechanics and Wind Engineering. Colorado State UNIVERSITY
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Don Mussared	Air Resource Specialists, Inc.
Dave Dietrich	Air Resource Specialists, Inc.
William White	Leader, Methods Application Group

Approach

Phase I

Model Selection and Evaluation

Phase II

Model Testing and Validation

Phase III

Model Merger and Technology Transfer

- **Approach designed to yield a complete product at the end of each phase.**
- **Provides logical break in development to allow managers to revise program direction.**
- **Product at end of Phase I is best available model based on current knowledge.**
- **Product at end of Phase II is improved model with quantitative confidence limits.**
- **At end of Phase III merger with FSCBG is complete and specialists have been trained.**

Phase I

Model Selection and Evaluation

A. ***Describe Physical Phenomena To Be Modeled***

B. ***Select Models for Evaluation***

C. ***Determine Availability of Input Variables.***

D. ***Evaluate Selected Models***

A. Describe Physical Phenomena To Be Modeled

- Description of early morning meteorology and spray drift behavior given in Appendix A. "Effects of Valley Meteorology on Forest Pesticide Spraying" by C. David Whiteman.

- Two distinctly different spray drift phenomena are identified.

- Early morning drift channeled into valleys is shown in Figure 1, Valley Drift.

- Mid-morning drift characterized by rising spray cloud being swept away from local area by gradient winds coupled to convective boundary LAYER as shown in Figure 2, Regional Drift.

- There have been many recent improvements in understanding the evolution of the valley's atmosphere during the inversion destruction period.

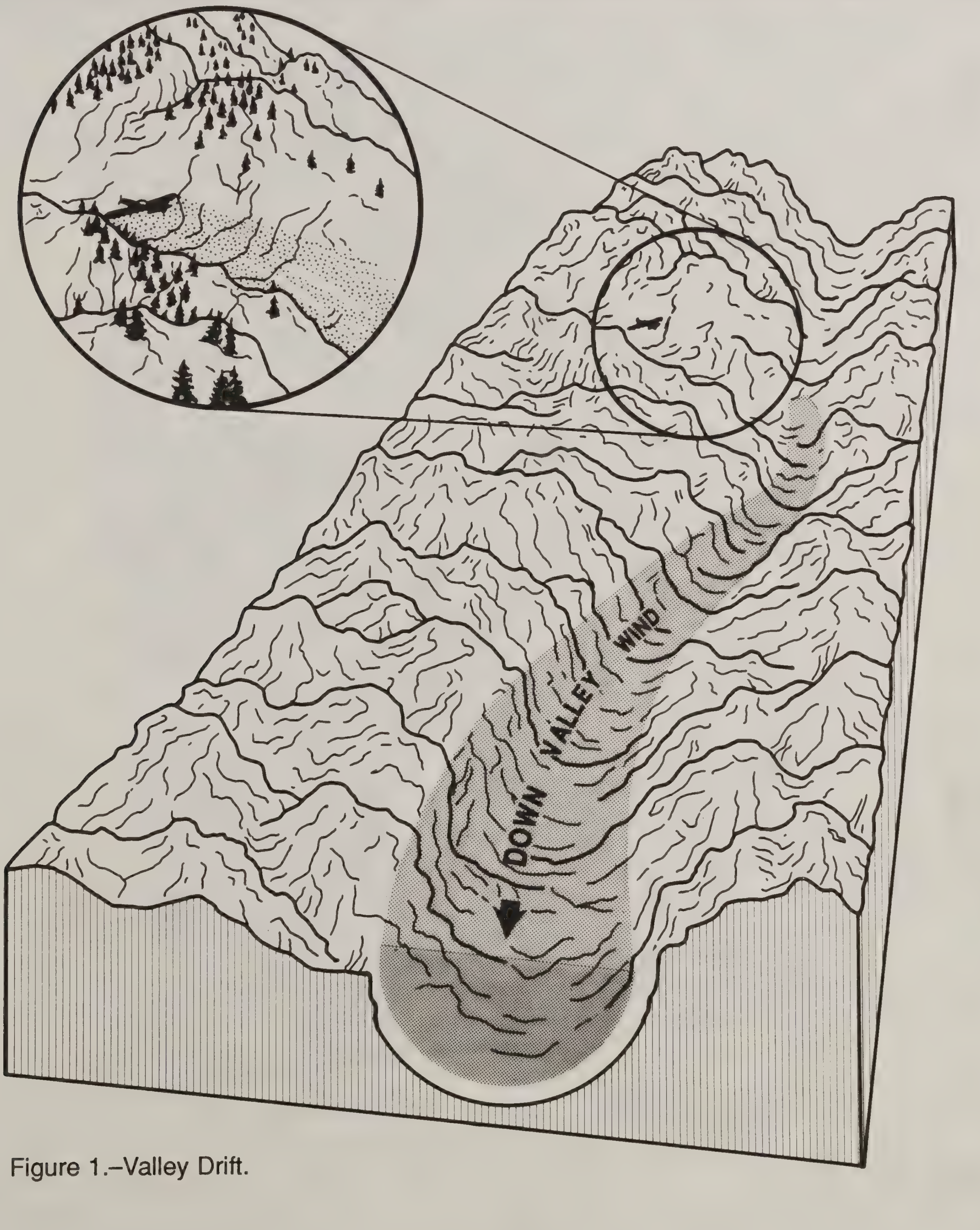

Figure 1.–Valley Drift.

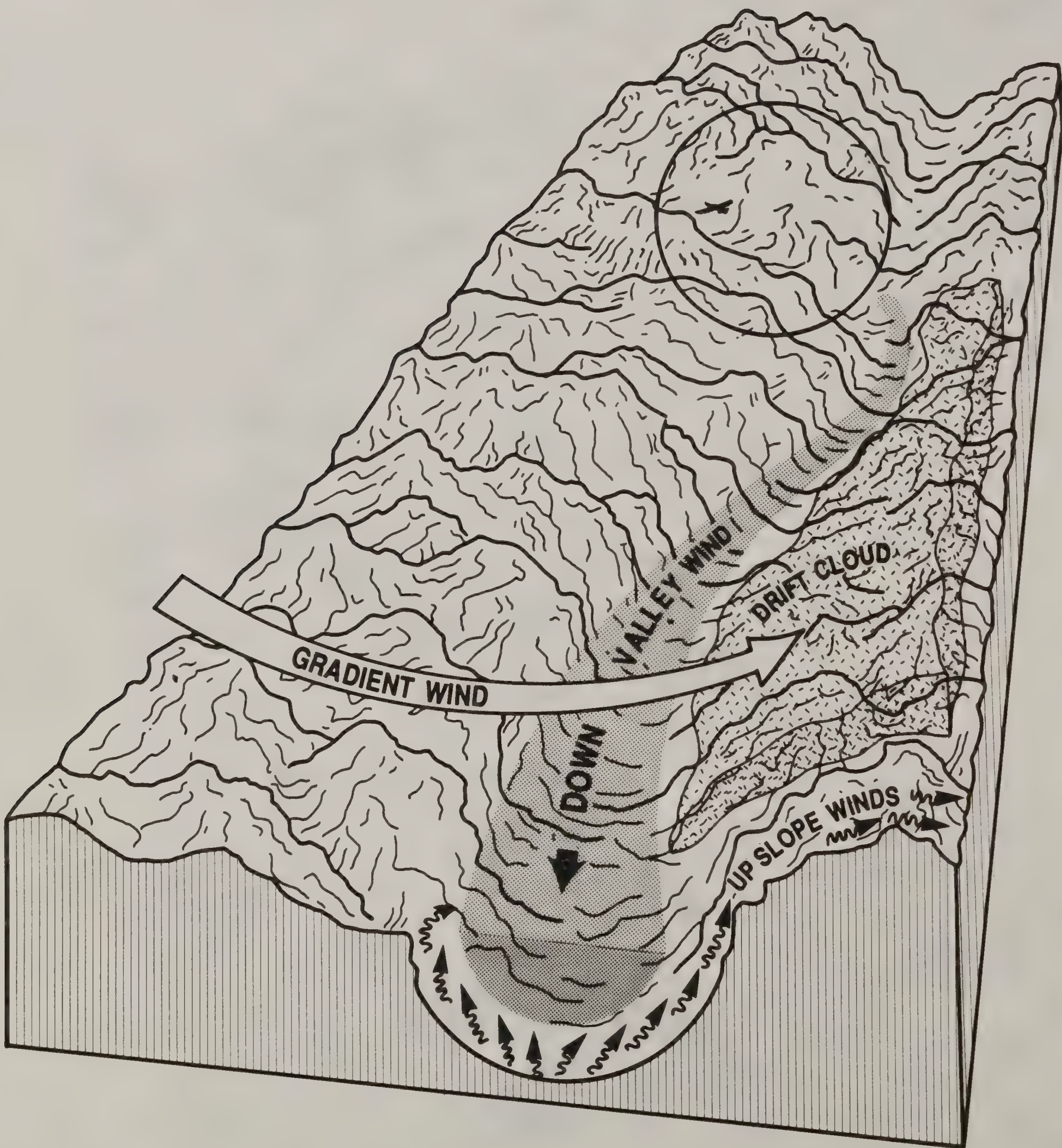

Figure 2.–Regional Drift.

B. Select Models for Evaluation.

- There are literally hundreds of Meso scale and complex terrain meteorological models.

- Models for consideration are limited to operational (as opposed to research) models that have documentation available.

- Desire models that use similar order of magnitude computer resources as current versions of AGDISP and FSCBG.

- Robert Meroney presents a classification system for complex terrain models and a review of the advantages and disadvantages of each class of model - Appendix B -.

- The two models selected for initial evaluation are TAPAS and VALMET.

- Other models will be considered after the initial evaluation of TAPAS and VALMET.

- Establish desired model results. Appendix C's "Discussion of Desired Model Output for a Combined FSCBG/Complex Terrain Model" by John W. Barry.

- Barry recommends current efforts be focused on VALLEY DRIFT rather than REGIONAL DRIFT.

- Comprehensive discussion of measuring drift and standard units and terms is given in Appendix D, "Criteria and Standards for Drift Sampling Forest Pesticide Sprays: by Robert Ekblad.

- Total flux is recommended for primary drift standard.

C. Determine Availability of Input Variables

- The Forest Service has not adopted a specific Geographic Information System (GIS).
- Most GIS systems are complex and are not likely to be used by the causal user.
- The Forest Service supports a digital Terrain Modeling (DTM) at Ft. Collins that can be accessed via the Data General System.
- DTM supports the Digital Elevation Model (DEM) terrain data format. It is set on a 30 meter grid and is suitable for analyzing valley drift. Other data formats are too coarse and must be developed from aerial photos.
- Over 50 percent of the National Forests are covered by DEM's.
- Inputs for solar driven models can be developed using longitude, latitude and computational methods to specify varying solar angle and azimuth.
- Simplifying assumptions that are conservative can be made to estimate source strength for stand-alone valley drift models. For example the spray area can be assumed to be a plenum chamber with all aerosols leaving at one plane at the same rate they are being introduced into the plenum chamber.
- Meteorological inputs for diagnostic models will require expert judgement and perhaps separate development.

D. Evaluate Selected Models

- Install selected models on computers at MTDC.
- Compare model results to existing drift data sets.
- Identify problems or special considerations in merging complex terrain models with AGDISP or FSCBG.
- Modify TAPAS or VALMET as necessary.
- Review additional models recommended by team or advisers.
- A comprehensive discussion of merging a complex terrain model with AGDISP or FSCBG is given by Teske in Appendix E. "Interfacing the Forest Service Spray Dispersal Models AGDISP and FSCBG to a complex Terrain Model".
- Train limited number of specialists in use of stand -alone complex terrain valley drift model (Optional).

Phase II

Model Testing and Validation

Phase III

Model Merger and Technology Transfer

Status – *July 1, 1990*

Phase I

	Percent Complete	*Planned Date for Completion*
A. Describe Physical Phenomena To Be Modeled	90	10/30/90
B. Select Models for Evaluation	75	10/30/90
C. Determine Availability of Input Variables	50	9/30/90
D. Evaluate Selected Models	10	3/30/91

Phase I

	Assignment	1990				1991			
		1	2	3	4	1	2	3	4
A. Describe Physical Phenomena to be Modeled.	***Ekblad***	x	x						
	Whiteman								
• Contract with PNW Battelle.	***Meroney***								
• Measure turbulence in local study area. Review Literature.	***Barry***								
• Convene panel of advisors.									
• Develop drift scenarios									
B. Select Models for Evaluation	***Whiteman***	x	x	x					
	Teske								
• Classify models	***Meroney***								
• Review Literature	***Ekblad***								
• Compare each class of model to requirements									
• Establish criteria for drift model									
• Recommend models for evaluation									
C. Determine Availability of Input Variables	***Ekblad***	x	x	x					
	Thompson								
• Review GIS systems									
• Review digital Terrain data bases									
• Develop simplifying assumptions for source strength									
• Develop meteorological, source and terrain inputs.									
D. Evaluate Selected Models	***Ekblad***	x	x	x	x	x			
	Thompson								
• Install selected models on local computers	***Mussard***								
	Whiteman								
• Review literature for drift data	***Teske***								
• Compare model results to existing drift data	***Barry***								
• Evaluate merging of complex terrain models to AGDISP and FSCBGF									
• Train other users									
• Modify models as required									
• Evaluate initial selection of models									

Note:

Years and quarters are calendar years

Phase II

	1991			
	1	2	3	4
Select Models and Scenarios for Validation	x	x		
Conduct Test		x	x	
Analyze Results and Report			x	x

Phase III

	1992			
	1	2	3	4
Merge Selected Models with FSCBG	x	x		
Technology Transfer			x	x

Appendix A

PNL-7332
UC-402

Effects of Valley Meteorology on Forest Pesticide Spraying

C. David Whiteman

April 1990

Prepared for the U.S. Forest Service
Missoula Technology and Development Center
under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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PNL-7332

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PNL-7332
UC-402

EFFECTS OF VALLEY METEOROLOGY ON FOREST PESTICIDE SPRAYING

C. David Whiteman

April 1990

Prepared for the
U.S. Forest Service
Missoula Technology and Development Center
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with the U.S. Department of Energy
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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Recent research has shown that many valleys, when undisturbed by external conditions such as cloudiness or high upper-level winds, undergo a regular diurnal evolution. Destruction of the nocturnal temperature inversion and reversal of the nocturnal down-valley flow occurs during a 3-1/2 to 5-hour period following sunrise, called the morning transition period. The processes responsible for temperature inversion breakup and wind system reversal are largely driven by the development of upslope flows in convective boundary layers (CBLs) that develop over the heated sidewalls. Aerial spraying of forest pesticides takes place in these growing CBLs. The important physical processes can be summarized:

- Spray released over the slopes before local sunrise will be carried down the slopes and down the valley but will remain fairly concentrated owing to reduced dispersion in the high stability atmospheric conditions. Non-deposited spray may adversely affect sensitive areas that may be located down-valley from the spray project.

- Upslope flows will form within a matter of minutes over sunlit slopes. Drift of a non-deposited plume will initially be upslope. If the spray plume escapes the boundary layer, however, or if the spraying occurs too high above the slope, it will be transported down the valley.

- The rate of development of the CBLs varies from location to location within the valley depending on time of sunrise, solar flux, surface energy budget, and temperature inversion destruction mechanism. When a boundary layer becomes deep and turbulent, spraying operations are no longer effective. This typically occurs first on the ridgetops and upper slopes. The lower slopes, because of the presence of the remnants of the nocturnal inversion above them, usually grow much more slowly and can be sprayed effectively much later in the morning. Late in the morning, the winds reverse to up-valley in the elevated remnants of the nocturnal inversion. Non-deposited pesticide will then drift up the slope and up the valley axis.

- After the temperature inversion is destroyed, the valley atmosphere will become part of a deep CBL. If coupled with strong winds aloft, the valley winds will be strong and turbulent, making conditions unsuitable for aerial spraying operations.

Recent gains in understanding of valley meteorology suggest that new modeling tools can now be applied to improve the planning and conduct of forest aerial spaying operations. Such tools may include digital topography models, solar shading algorithms, inversion breakup models, and flight path optimization models. Simple dispersion models could be modified to provide useful planning tools for forest spraying operations, and a long-term program could be initiated to apply recent boundary-layer growth models to three-dimensional topography.

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1.0 INTRODUCTION

Pacific Northwest Laboratory conducted this study for the Missoula Technology and Development Center of the U. S. Department of Agriculture's Forest Service. The purpose of the study was to summarize recent research on valley meteorology during the morning transition period and to qualitatively evaluate the effects of the evolution of valley temperature inversions and wind systems on the aerial spraying of pesticides in National Forest areas of the western United States.

Aerial spraying of pesticides and herbicides in forests of the western United States is usually accomplished in the morning hours after first light, during the period known to meteorologists as the "morning transition period." The morning transition period is the post-sunrise period when the nocturnal down-valley flows are reversed to daytime up-valley flows and when the nocturnal temperature inversions are destroyed. The spraying continues until convective boundary layers and upslope flows develop sufficiently to render it difficult to place the spray where needed in the canopy. On an undisturbed clear day, the spraying must be terminated in mid to late morning. The normal sequence of meteorological events during the morning transition period is now well known, although the timing of these events varies significantly from valley to valley and from location to location within the same valley. This document describes the key physical processes that occur during the morning transition period on undisturbed days and the qualitative effects of these processes on the conduct of aerial spraying operations. Since the timing of valley meteorological events may be strongly influenced by conditions that are external to the valley, such as strong upper-level winds or the influence of clouds on the receipt of solar energy in the valley, some remarks are made on the qualitative influence of these processes. Section 4 of this report suggests ways to quantify some of the physical processes to provide useful guidance for the planning and conduct of spraying operations.

2.0 PHYSICAL PROCESSES

In this section, we summarize valley temperature inversion destruction observations collected in a number of Colorado valleys, pointing out typical characteristics of the meteorology of these valleys and the physical processes that must be included in realistic spray dispersion models simulating the inversion destruction period. In the last 10 years it has become clear that the inversion breakup patterns first observed in Colorado valleys in the 1970s are typical of patterns found in many other mountainous regions (Whiteman 1990), so that the understanding gained in the study of Colorado valleys is expected to be of widespread applicability. The following summary deals with conditions when upper winds are weak and weather conditions are undisturbed by large-scale traveling storm systems, such that the circulations within the valley are entirely locally produced. These local circulations are thermally driven, forced by pressure differences that arise owing to different rates of heating and cooling between the valley and its surroundings and between different locations within the topography. In such conditions the two main classes of local circulations are the up- and down-valley flows and the up- and down-slope flows (Figure 1) that have long been recognized in mountainous regions.

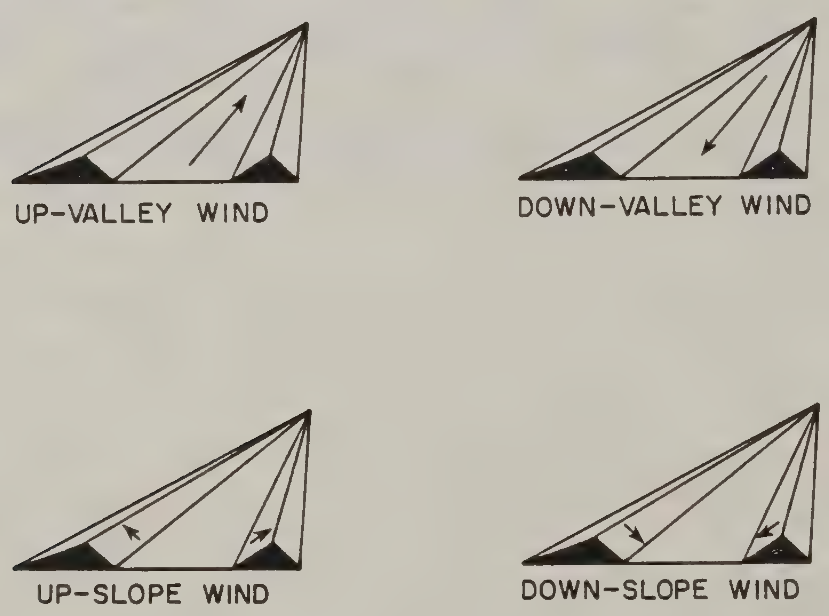


FIGURE 1. Wind System Nomenclature

2.1 Buildup of Valley Temperature Inversions

Cold air drains off the ridgetops and slopes of a valley during nighttime and collects in the valley, forming a surface-based temperature inversion (Figure 2a). In such an inversion, the coldest temperatures are found adjacent to the surface, and temperatures increase with altitude until the top of the inversion is reached. In the high-elevation, continental, mountainous western United States, the cooling power is strong enough on most clear nights to produce a surface-based temperature inversion that extends through the entire valley depth. Winds within the temperature inversion blow down the valley axis, although there are shallow downslope flows over the inclined sidewalls. The coldest temperatures and the strongest inversions generally occur at astronomical sunrise. This nocturnal inversion is generally destroyed following sunrise (Figures 2b through 2d), as solar energy provides the necessary heating at the surface. The ground or vegetative canopy absorb solar radiation and, in turn, heat the adjacent air. As the air warms it becomes less dense and eventually moves upward replacing cooler denser air in a process referred to as convection. Further details regarding the physical processes leading to the valley wind and temperature structure evolution during this period follow, illustrated by the Colorado observations.

2.2 Breakup of Valley Temperature Inversions

Temperature inversions in Colorado valleys are destroyed after sunrise following one of three patterns (Whiteman 1982) of temperature structure evolution (Figure 3). Note that Figure 3 uses potential temperature rather than actual temperature for the abscissa; potential temperature is preferred since actual temperature is a non-conservative variable under vertical motion because of the dependence of temperature on pressure. For those unfamiliar with this new variable, to a first approximation simply consider potential temperature to be actual temperature, and consider a constant potential temperature layer to be a well-mixed or convective boundary layer (CBL).

The first pattern, observed in the widest valley studied, approximates inversion destruction over flat terrain, in which the nocturnal inversion is destroyed after sunrise by the upward growth from the ground of a warming CBL. The elevated inversion or cold pool is eroded from the bottom but does not descend. The second pattern, observed in snow-covered valleys, differs significantly from the first. Here the growth of a CBL, which begins after sunrise, is arrested once the CBL has attained a depth of 25 to 50 m. The inversion is then destroyed as the top of the nocturnal inversion descends into the valley. Warming of the central region of the cross section is consistent with adiabatic subsidence heating produced by the descending motions. The third pattern of temperature structure evolution was observed in all of the valleys when snow cover was not present and describes the majority of case studies observed in field experiments. In this pattern, inversions are destroyed by a combination of two processes: the

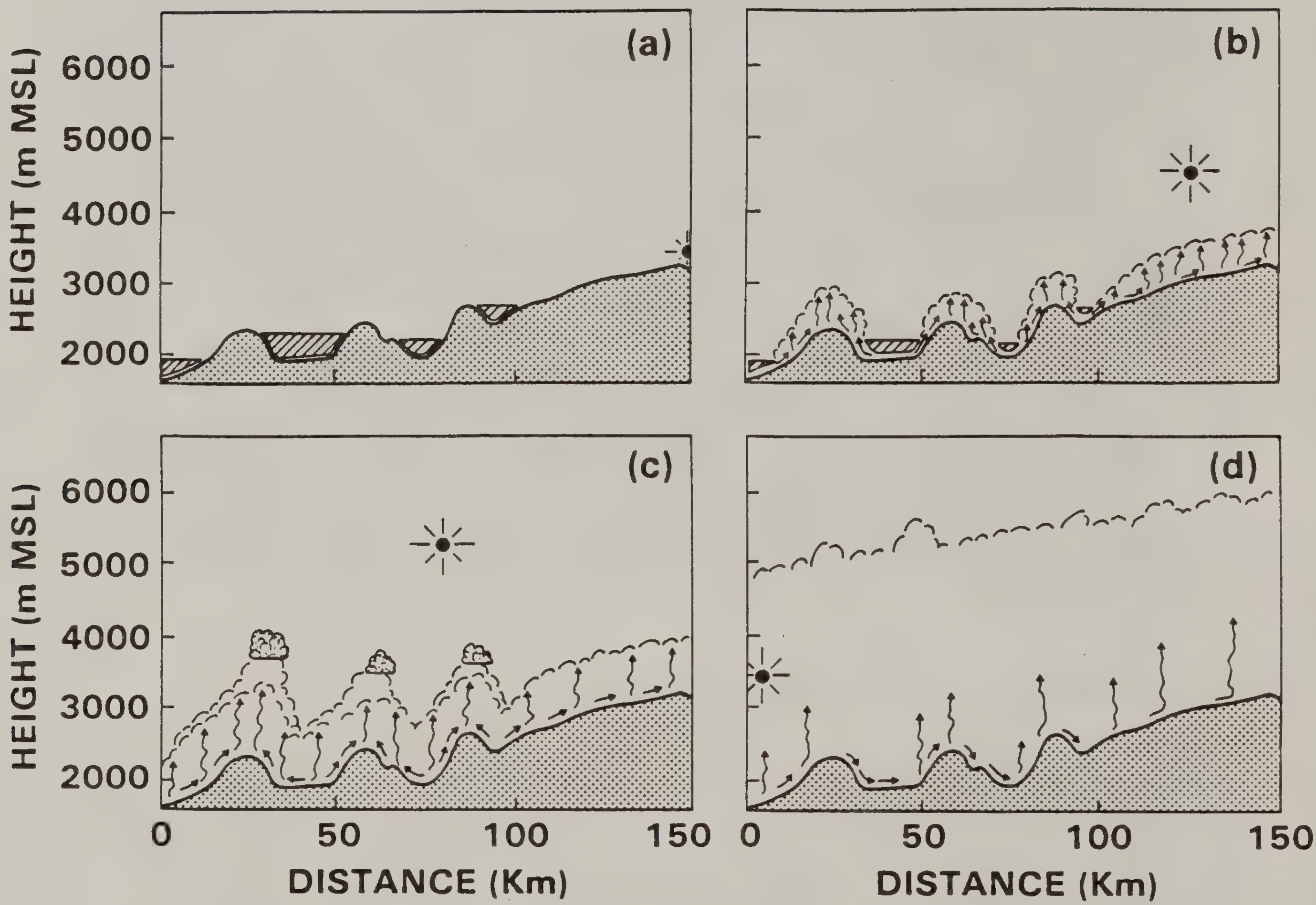
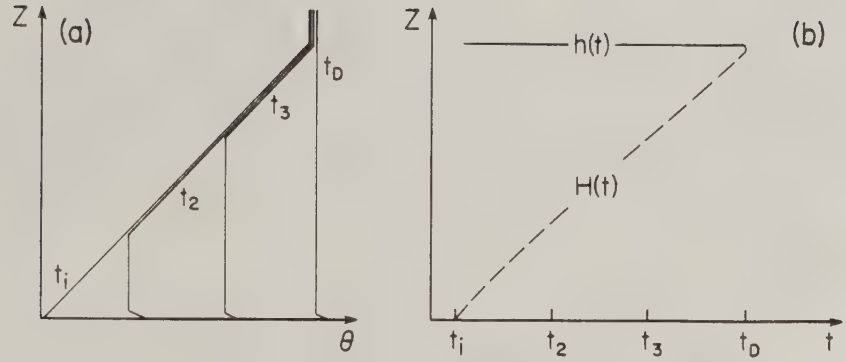
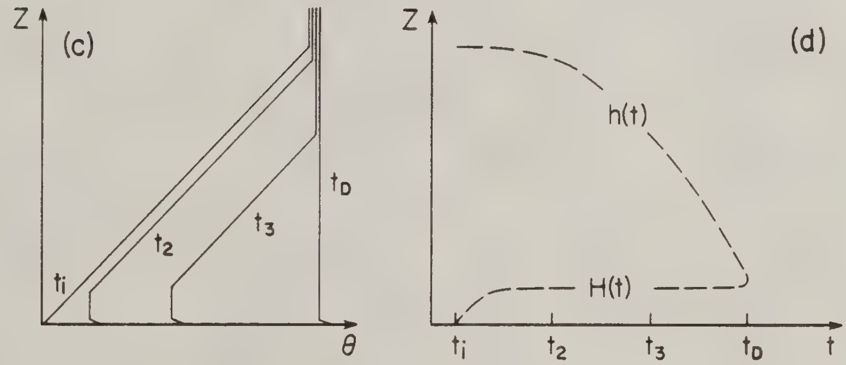


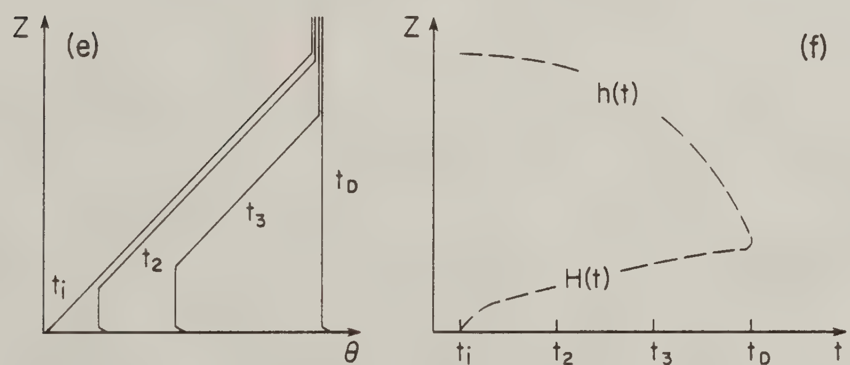
FIGURE 2. Schematic Depiction of Wind and Temperature Structure Evolution in Valleys. (a) At sunrise, the cold air has built up in the valley depressions forming surface-based temperature inversions. (b) After sunrise, convection and upslope flows begin to form over the heated slopes. Over the ridgetops, the convection results in rapid boundary layer growth, while, in the valley, the depth of convection is constrained by the overlying remnants of the nocturnal inversion. (c) By midday, the valley temperature inversions are destroyed and convection occurs in turbulent boundary layers over all heated surfaces. (d) By late in the day, the convective boundary layer reaches its maximum height over the mountain range and weak downslope flows occur over valley sidewalls that become shaded by the surrounding topography.



Pattern 1. Growth of CBL.



Pattern 2. Descent of inversion top and arrested growth of CBL.



Pattern 3. Descent of inversion top and continuous growth of CBL.

FIGURE 3. Three Patterns of Temperature Structure Evolution with Height (z) and Time (t) during the Inversion Breakup Period. Potential temperature profiles (θ) are on the left, and time-height analyses of convective boundary layer height (H) and inversion top height (h) are on the right.

continuous upward growth from the valley floor of a warming CBL and the continuous descent of the top of the nocturnal temperature inversion. Again, as for the second pattern of inversion destruction, warming of the elevated inversion layer above the CBL is caused by vertical advection, i.e., by simple sinking of warm air from aloft. In the Colorado valleys studied, the time required to break an inversion and establish a neutral atmosphere within the valley was typically 3-1/2 to 5 hours after sunrise. Temperature structure evolution during clear, undisturbed weather was surprisingly uniform from day to day and from season to season. Thus, in pesticide spraying work, one may be fairly confident of observing typical inversion breakup in a pre-spray campaign data collection program in undisturbed weather.

The common element of all three patterns of temperature structure evolution is the development of a CBL over the valley floor after it is illuminated by direct sunlight. Observations taken from the sidewalls also show the development of a CBL after direct sunlight illuminates the sidewall. Because of the shading effects of surrounding topography, the different valley surfaces can be illuminated at significantly different times, thus affecting the initiation of CBL growth. The temperature structure of the sidewall CBL is similar to that over the valley floor, but winds blow up the sidewall CBL at speeds of up to 3 m/s.

Five different temperature structure layers have been observed during the temperature inversion destruction period. Above the valley floor CBL and the sidewall CBL just mentioned is the stable core of the potential temperature inversion. This layer represents the remnants of the nocturnal surface-based valley temperature inversion. A layer above the stable core, to be called the 'neutral layer' in the subsequent text, appears to be part of a large-scale convective boundary layer that forms over the western slope of the Rocky Mountains. Such an intermediate circulation might form above any valley that is cut into the side of a mountain range. Above this layer is the free atmosphere.

Each of the five temperature structure layers, identified primarily by their potential temperature structure, can also be identified by the winds that prevail within them (see Figures 4, 5, and 6). During inversion destruction, the CBLs over the valley floor and sidewalls contain winds that blow up the floor of the valley and up the slopes. The neutral layer above the valley inversion has winds that blow up the inclined western slope of the Rocky Mountains during the day. Winds in the stable core typically continue to blow down-valley after sunrise until the stable core is nearly destroyed. Winds in the stable free atmosphere may blow from any direction with speeds determined by synoptic-scale pressure gradients. Despite variability in the strength and timing of reversal of the winds, the temperature structure evolves uniformly from day to day in individual valleys.

On the basis of the wind and temperature observations summarized above, an hypothesis has been developed to explain the temperature structure evolution (Figure 7). Since energy is required to change the temperature structure, and

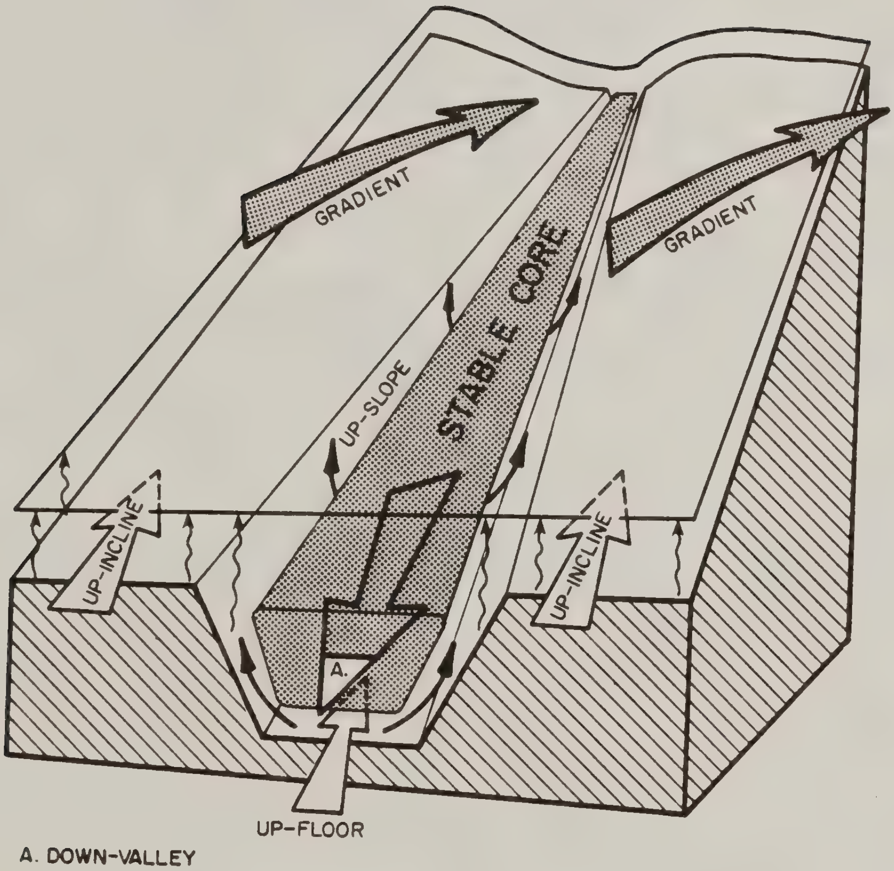


FIGURE 4. Typical Mid-morning Wind Structure Over and Within a Deep Valley on the Western Slope of the Rockies, Illustrating the Five Interrelated Wind Systems Identified in Field Studies.

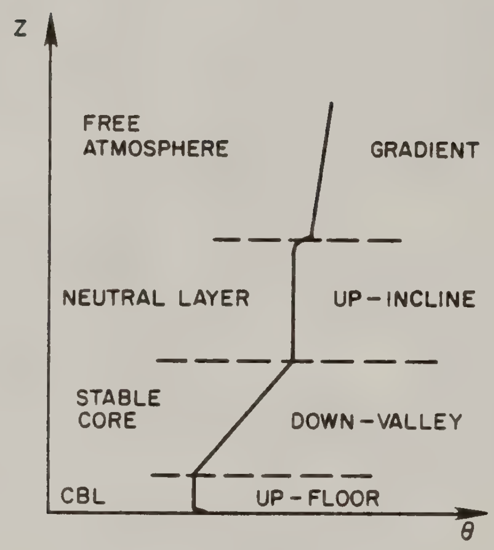


FIGURE 5. Relationship Between Temperature Structure Layers and Wind Systems. The temperature structure represents a typical mid-morning sounding from the floor of a deep valley.

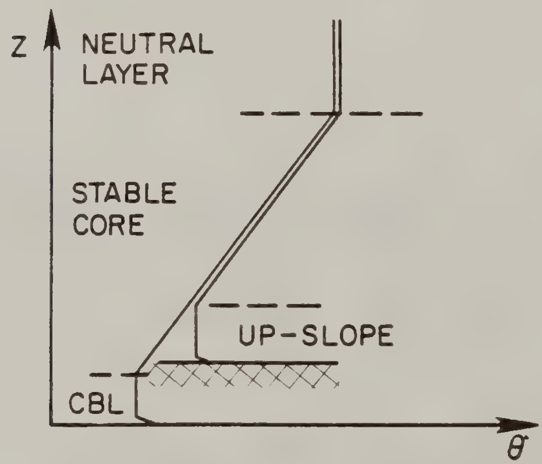


FIGURE 6. Dual Soundings from a Valley Floor and a Valley Sidewall Illustrating the Upslope Flow Found Within the CBL Over the Sidewall.

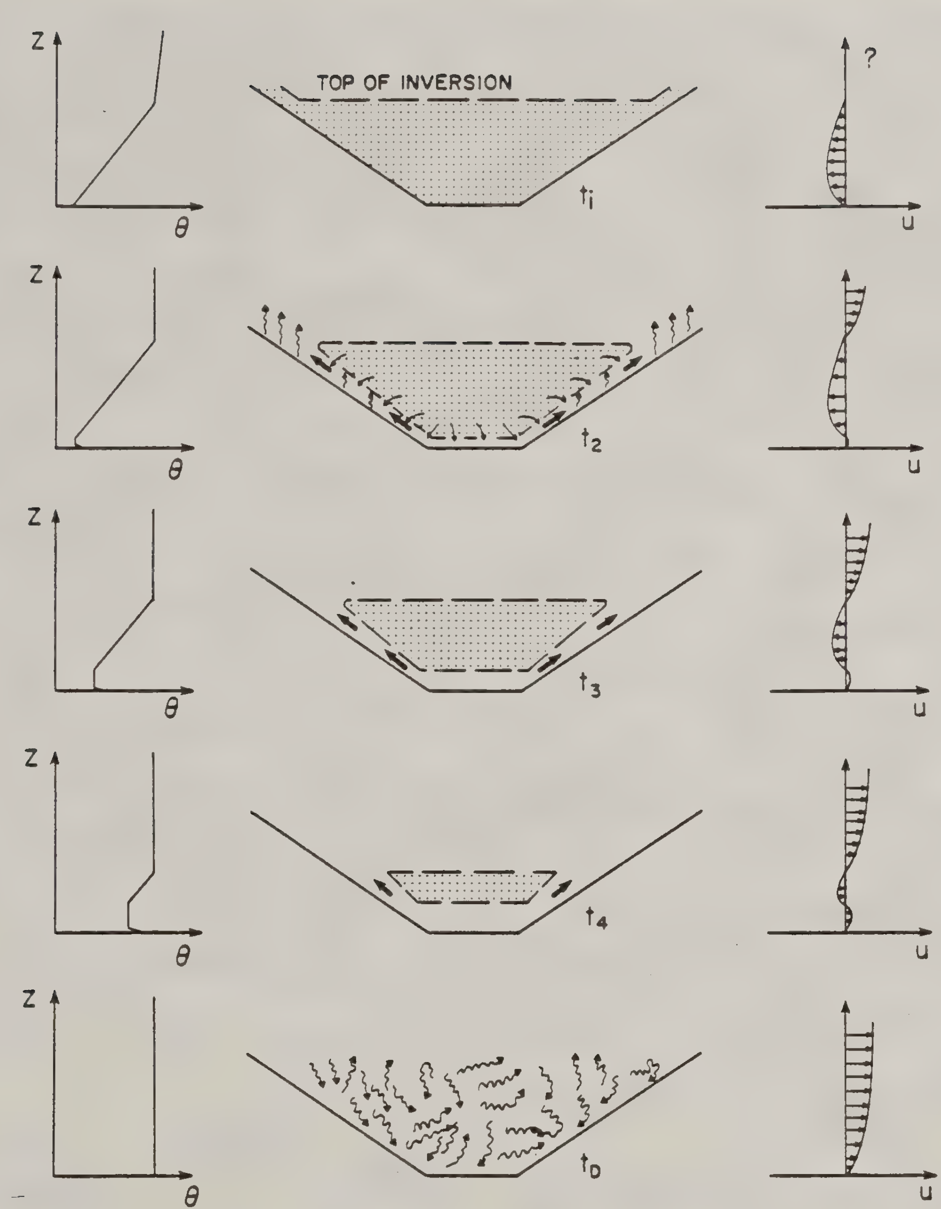


FIGURE 7. Illustration of the Hypothesis of Inversion Destruction. In the center of the diagram cross sections of a valley are shown at times t_i, t_2, t_3, t_4, and t_D. On the left are corresponding potential temperature profiles as taken from the valley center. On the right are corresponding up-valley wind components (u) as a function of height. At sunrise, t_i, an inversion is present in the valley. At t_2, a time after sunlight has illuminated the valley floor and slopes, a growing CBL is present over the valley surfaces. Mass and heat are entrained into the CBLs from the stable core above and carried up the sidewalls in the upslope flows. This results in a sinking of the stable core and growth of the CBLs (t_3 and t_4) until the inversion is broken (t_D) and a turbulent, well-mixed neutral atmosphere prevails throughout the valley depth. Down-valley winds continue to blow in the stable core during the inversion breakup period. Winds in the CBL below and in the region above the stable core often blow up-valley during this same period.

the change begins at sunrise, it is reasonable to propose that solar radiation is the driving force. A fraction of the solar radiation, received on the valley floor and sidewalls, is converted to the sensible heat flux that provides energy to the valley atmosphere. Sensible heat flux from a surface, as over flat terrain, causes a CBL to develop over the surface. Mass and heat are entrained into the CBL from the stable core above. Mass entrained into the valley floor and sidewall CBLs, however, is carried from the valley in the upslope flows that develop in the CBLs over the sidewalls. This removal of mass from the base and sides of the stable core causes the elevated inversion to sink deeper into the valley and to warm adiabatically during its subsidence and decreases the rate of growth of the underlying CBLs. The rate of warming depends directly on the rate of energy input into the valley atmosphere. This energy may be used to deepen the CBLs or to move mass up the sidewalls, allowing the stable core to sink. From this hypothesis a thermodynamic model of temperature inversion destruction has been developed (Whiteman and McKee 1982). This thermodynamic model forms the basis for parameterizations of inversion breakup in a valley air pollution model called VALMET (Whiteman and Allwine 1985).

Research in Colorado's Brush Creek valley in 1984 (Whiteman 1989, Bader and Whiteman 1989) identified a further physical process that may affect plume dispersion in narrow north-south oriented valleys. There, a cross-valley advection occurred during times of the day when one of the sidewalls was strongly illuminated by the sun and the other sidewall was in shadow or received weak solar heating. The effect of the cross-valley advection was to transport elevated plumes toward the strongly illuminated sidewall. This effect has been seen in other valleys (e.g., Urfer-Henneberger 1970) and has been investigated theoretically by Gleeson (1951).

2.3 The Valley Heat Budget

Moist surface conditions, cloudiness, or high albedo owing to snow cover may change the surface energy budget components so that sensible heat flux is reduced. In these conditions, inversion destruction will be delayed or an inversion may persist all day (see, e.g., the Yampa Valley observations of Whiteman and McKee 1982). These conditions are often advantageous for forest spraying, since the boundary layers over the sidewalls develop more slowly on such days, and acceptable spraying conditions persist much longer into the morning and afternoon than would be the case with clear skies and strong sensible heat flux.

Further, in a valley of complicated topography, the propagation of shadows from surrounding topography will ensure that some of the valley's slopes may be in shadow while others are in sunlight. Thus, we may speak of local sunrise times at points in the valley being later than the time of astronomical sunrise. Often the propagation of shadows is quite predictable to the casual observer, viz., the slow propagation of a shadow down one of the sidewalls, but in deeply dissected topography the propagation of shadows may be quite complicated, especially where the valley axis follows a sinuous course (see, e.g., Figure 8).

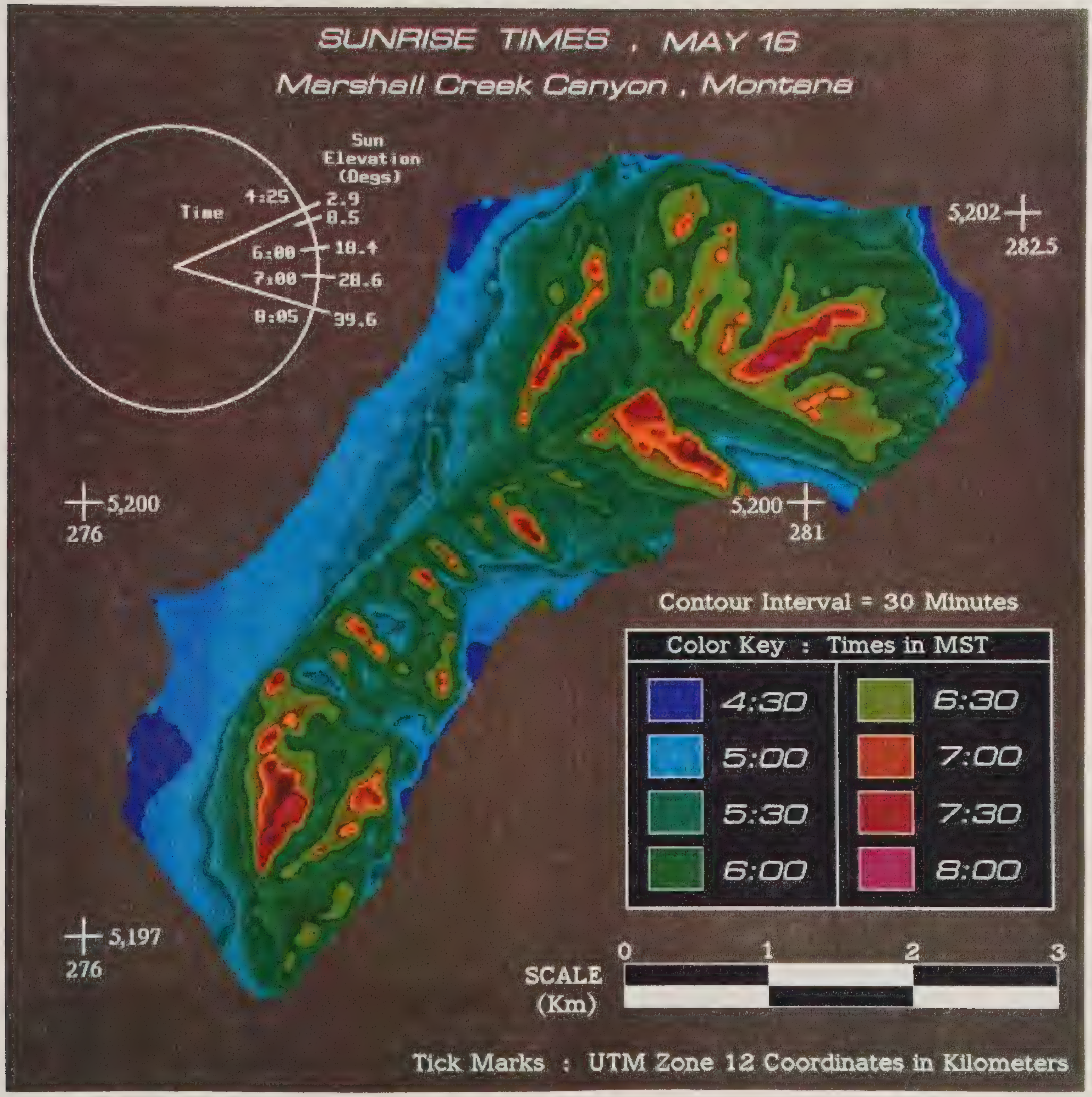


FIGURE 8. The Varying Times of Local Sunrise (Mountain Standard Time), Shown Here for Montana's Marshall Creek Canyon on May 16 Will Produce Spatial Contrasts in Boundary Layer Growth. Quantitative information from solar radiation and solar shading models such as the one shown here could be used to plan and optimize forest pesticide spraying operations in the country's national forests.

3.0 GENERAL CONSIDERATIONS: PESTICIDE DISPERSION IN FORESTED VALLEYS

The valley inversion destruction mechanism outlined above has important implications for the dispersion of pesticide sprays. These implications will be investigated first by assuming that the nocturnal inversion at sunrise contains pesticides that have been sprayed along the valley's axis in the mid-valley atmosphere. Other assumptions will be made subsequently. Typically, at sunrise, the plume would be carried down the valley in the nocturnal drainage flows, undergoing both vertical and horizontal dispersion. It is of interest that horizontal dispersion in these flows is known to be much greater than over flat terrain (Start et al., 1975) - a factor which may decrease the concentrations of a plume transported over a valley centerline relative to that over a plain. This important factor is, however, counterbalanced somewhat by the fact that the plume is channeled by the valley and that the plume centerline may directly impact an elevated terrain feature. We will focus initially on the dispersion of the pesticide on a valley cross section (Figure 9). After sunrise a convective boundary layer forms over the valley floor and sidewalls (Figure 9a). The subsequent dispersion in the stable core will be affected by two competing processes -- the sinking of the stable core and the growth of the CBL. The three inversion breakup patterns discussed above have the following dispersion implications:

1. Pattern 1 - Growth of convective boundary layer (Figure 9b): Pure growth of a CBL will result in the fumigation (Hewson et al., 1961) of a spray cloud at the valley floor as the CBL grows upward into the stable core. This process is favored when the slope flows are ineffective in removing mass from a valley and will thus occur in very wide and/or shallow valleys.

2. Pattern 2 - Sinking of stable core (Figure 9c): Failure of the CBL to grow once it has formed over the valley floor and sidewalls results in inversion destruction by sinking of the stable core. Thus, the spray cloud sinks into the top of a shallow mixed layer, producing high concentrations at the ground. The spray plume, once entrained into the CBL, is advected up the sidewalls and dispersed into the neutral layer aloft. This process is favored for narrow-to-wide valleys when sensible heat flux is weak.

3. Pattern 3 - Combination (Figure 9d): A combination of CBL growth and stable core descent results in the sinking of the spray cloud into the top of a growing mixed layer. Spray concentrations should be intermediate between the two previous cases. This pattern is the most common one in Colorado Mountain valleys.

The above discussion focuses on plume dispersion on a valley cross section. However, winds in the stable core, as mentioned above, blow down the valley until the inversion is nearly broken. Thus, pesticide sprayed into the stable core encounters a stable environment where diffusion is quite limited and will be carried down the valley, often toward populated or other sensitive areas.

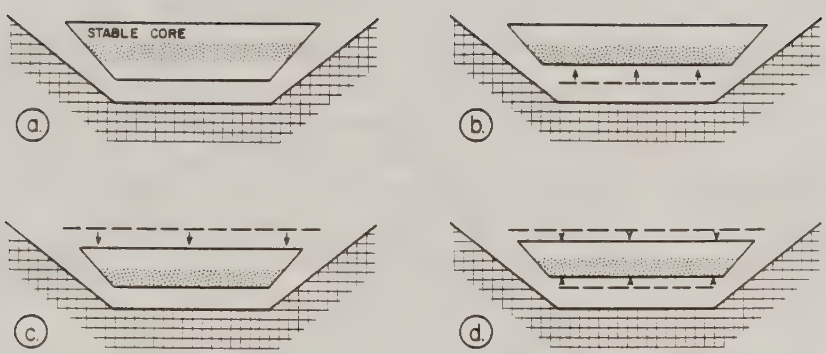


FIGURE 9. Dispersion Implications of CBL Growth and Inversion Top Descent.

Actual forest pesticide spraying, rather than occurring at an elevated position in the mid-valley atmosphere, is conducted by spray aircraft over the sidewalls above the forest canopy. Thus, after local sunrise the spray is released into the growing CBL, rather than into the stable core. When this boundary layer is shallow and the upslope winds within the layer are weak, the pesticide plume will deposit well in the canopy, aided by the downward motions from wingtip vortices. Any non-deposited chemical will generally drift up the slope and concentrations will be decreased by mixing caused by the turbulent winds within the upslope-flowing layer. A different situation arises, however, when the pesticide is sprayed later in the morning into a deep, fully-developed slope boundary layer. Then, flying conditions will be rough, and the spray plume may be broken up by strong convective eddies. A smaller proportion of the plume will be deposited and a larger drift will occur. Fortunately, however, this drift will be up slope and pesticide will be well mixed through the deep layer so that concentrations will be low. The drift of the plume will rarely be toward sensitive population centers, since such centers are generally located down-slope on the valley floor. The most ideal spraying conditions should occur after the slope is illuminated by the sun, but before the convective boundary layer becomes deep and fully developed. The CBL on the ridgetops and at the upper levels of the sideslopes develops very rapidly after sunrise, since the stable core descends into the valley and these convective layers are not constrained by an overlying inversion layer. As these boundary layers develop, mixing may increase the exposure of the ridgetops to strong upper-level winds, further decreasing the chances of getting pesticide deposition on target vegetation.

4.0 CONCLUSIONS REGARDING FOREST PESTICIDE SPRAYING

The above description of valley meteorology during the morning transition period results in the following implications for forest spraying activities:

• Spray released before sunrise or over shaded slopes will be released into shallow stable boundary layers over the slopes. Drainage flows in these boundary layers will be downslope. The overlying down-valley flows typically superimpose a down-valley wind component on these layers, so that any drift of the spray will move downslope and down-valley. Pre-sunrise spraying may adversely affect population centers or sensitive areas that are downslope or down-valley during this time period. When plume impacts occur, concentrations may be quite high because of the poor diffusion environment along the transport path in the remnants of the strong nighttime inversion.

• Initially, shallow CBLs form over sunlit slopes. Shortly after they are sunlit (typically 10 to 15 minutes), an upslope flow will form. Drift of a non-deposited plume will then be upslope. If the plume escapes from the boundary layer (or if the spraying occurs too high above the slope), it will be transported down the valley in the remnants of the stable core.

• Convective boundary layers develop rapidly over the ridgetops and upper slopes after they become sunlit, because they are not capped by the strongly stable nocturnal inversion. Especially rapid CBL development may occur over the upper slopes that face the morning sun. When upper winds are moderate or strong, growth of the CBLs will bring the stronger winds down onto the upper slopes. The upper slopes would then become more and more turbulent, with the normal thermal convection processes being supplemented by transport of horizontal momentum from aloft. The rate of CBL development over the upper slopes will strongly affect the spraying environment there.

• Once temperature inversion destruction begins, the top of the temperature inversion will sink into the valley, exposing more of the upper slopes to intense CBL development. Winds within the stable core during this time will continue to blow down the valley, but the speed will typically be decreasing until, just before the inversion is destroyed (3-1/2 to 5 hours after astronomical sunrise on a clear day), the winds will switch to up-valley throughout the valley's volume.

• During the inversion destruction period, boundary layers on the lower slopes will be growing much more slowly because of the strongly stable layer (the remnants of the nocturnal inversion) that overlies them.

• Given the above processes, rates of CBL development depend strongly on the local amount of insolation (which varies from place to place within the valley), the surface energy budget, and the overlying temperature structure. The ridgetops and upper slopes should be sprayed first, because the dispersion environment there rapidly becomes too turbulent for continued spraying. The spraying environment on the lower slopes, in contrast, is suitable for spraying

for a much longer time. Spraying conditions can be quite different on opposing slopes during the morning transition period, especially in north-south oriented valleys where the opposing slopes have quite different heating functions. The east-facing slope will receive solar input earlier, the CBL will develop earlier and more rapidly, and the differential heating of the two slopes may result in a cross-valley flow toward the heated slope.

• After the temperature inversion is destroyed, the valley becomes well coupled with the winds aloft. If these winds are weak, a thermally driven up-valley circulation will prevail within the valley. The absence of a strong capping inversion above the surfaces will result in a deep and turbulent CBL over all the valley's surfaces. If the upper winds are strong, they may superimpose their own wind direction on the valley, and winds may be correspondingly stronger and more turbulent, making conditions unsuitable for aerial spraying operations.

5.0 RECOMMENDATIONS

Our present understanding of valley meteorology during the morning transition period has progressed to the point where some useful planning tools could be constructed to optimize a forest pesticide spraying campaign. Simple models could be developed for use in the field to optimize the vectoring of spray planes so that spraying could be accomplished in the most suitable locations within a drainage area before convective boundary layers became too deep and strong. The area of effective pesticide coverage in a given spray campaign could be optimized by such a model. Digital topography models and solar shading algorithms could be developed to aid in this determination. Inversion breakup models and some simple air pollution dispersion models (Whiteman and McKee 1982, Whiteman and Allwine 1985) could be modified for support of forest spraying campaigns. Finally, some promising models of boundary layer growth on slopes have been formulated in the last several years that could be applied to the forest spraying problem. A model by Brehm (1986) was published in 1986, while two recent models, one by Dr. U. Schumann at the German Aerospace Research Establishment and one by Dr. J. Egger of the University of Munich, are presently in press. These models could be formulated in three dimensions, raising the possibility of using actual digital terrain, solar shading, and boundary layer growth models in a single package. Such boundary layer growth models have not yet been tested in real valleys, so that field experiment campaigns should be an important component of future work.

While the approaches mentioned in the previous paragraph could be applied now, several key research questions remain that will need to be addressed in order to make further progress. Some of these issues are being addressed now in ongoing research funded by the U.S. Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program and in other federal programs. Very little work has, so far, been accomplished dealing with variations in surface energy budgets over complex terrain areas. Such energy budgets, which have a strong influence on the development of local circulations and growth of boundary layers, will be affected by clouds. Few studies have dealt with the influence of clouds. Further, much meteorological research remains to be done on forest canopies and their effects on valley heat budgets and locally developed circulations. Finally, the influence of external processes on valley circulations has not received enough attention. Key research questions involve the coupling of valley and above-valley circulations. This coupling is a quite frequent phenomenon in the valleys of the western United States.

The recent improvements in understanding of the evolution of the valley's atmosphere during the inversion destruction period could be incorporated in algorithms, planning tools, simple models, or numerical models, and should provide an improved basis for the planning and conduct of future aerial spraying operations.

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Appendix B

SUBJECT: REVIEW AND CLASSIFICATION OF COMPLEX TERRAIN MODELS FOR USE WITH INTEGRATED PEST MANAGEMENT PROGRAM SPRAY MODELS

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I. INTRODUCTION

An important goal of the Forest Service's Integrated Pest Management Program is to develop effective numerical advisory programs. Such programs advise personnel when effective aerial spraying for pest control can occur over complex terrain without atmospheric dispersion and deposition outside the target area. The effect of complex terrain and valley drainage meteorology must be incorporated into aerial spray models such as AGDISP or FSCBG developed by the Forest Service for relatively flat terrain.

A review of currently available complex terrain models is provided to select software which might provide such valley drainage and complex terrain information for incorporation into the Forest Service models. The review does not propose to identify new computational research areas but to determine which models are ready for incorporation into the Forest Service management program. The review document contains:

a) An examination of the relative merits of phenomenilogical models, objective analysis models, linearized models, shallow layer models, or primitive equation models,

b) Examples of appropriate models in each category together with appropriate references and availability of source code, and

c) A critique of the various models, together with recommendations concerning model development or revisions necessary for use by the Forest Service aerial spray program.

II. BRIEF HISTORY OF PREDICTION OF DISPERSION IN COMPLEX TERRAIN

The need to estimate reliably the impact of emission sources in regions of complex terrain for decision-making purposes remains a "key challenge" to the meteorological community (Egan and Schiermeir, 1985). No adjustments for terrain influence on pollutant concentrations were made until the 1970s, when it became necessary to use diffusion models as a requirement of the U.S./ Clean Air Act and its amendments. Increased concentrations in rugged terrain can result from plume impingement on high terrain, pooling in valleys, drainage towards population centers, or persistence due to channeling. AMS, EPA, DOE, and EPRI have all supported workshops and research programs dedicated to a better understanding of dispersion in rugged terrain. Prominent among the coordinated analytic, field and numerical studies have been EPA's Complex Terrain Model Development (CTMD) Program, EPRI's Plume Model Validation and Development (PMV&D) study, and DOE's Atmospheric Studies in Complex Terrain (ASCOT). These field studies have added substantially to the understanding of drainage and slope flows, stratified flow over and around isolated hills or ridges, and narrow valley circulations.

An excellent review of meteorological processes over complex terrain and the state-of-the-art of analytical, physical and numerical modeling was provided during the AMS Workshop on Current Directions in Atmospheric Processes Over Complex Terrain, October 1988 in Utah. The results of this workshop will soon appear in an AMS Monograph of the same name, and frequent reference to draft chapters were made during this review.

III. MODEL CLASSIFICATION

Dispersion prediction codes or algorithms for flow over terrain can be grouped into four flow categories of increasing flow complexity. These are a) flows for steady-state, straight line winds over homogeneous flat terrain, b) flows where plume impact or contact with the face of hills or ridges occurs due to terrain rising to intercept an elevated plume, c) flows which are diverted, accelerated or decelerated due to variations in surface contours, temperature, and roughness in the absence of separation or recirculation, and d) flows where backflows and recirculation may occur as a result of obstacle separation, valley drainage circulations, sea/lake circulations, etc.. Parallel with these flow categories one can identify seven categories of numerical modeling:

i) Gaussian plume models,
ii) Hill intercept models,
iii) Phenomenalogical models,
iv) Mass consistent or objective analysis models,
v) Depth integrated models,
vi) Linear perturbation models, and
vii) Full primitive equation models.

IV. MODEL DESCRIPTION AND CRITIQUE

It will not be possible to review all complex terrain models here. A comprehensive list of models by name, type and author will be provided in tables. Prominent members of each category will be described to identify the advantages and disadvantages of each approach. Copies of almost all model source codes are available by request or purchase.

A. Gaussian Plume Models

Codes developed to handle more or less homogeneous terrain situations frequently employee simple gaussian distribution models. Candidate models include many of the EPA UNAMAP models. A list of some 35 such models is noted in Table 1a extracted from the report by Lewellen and Sykes (1985). The table has been modified to include more recent models. These models are sufficiently simple that they are frequently used for initial estimates of transport and diffusion out to 10 miles. These models are limited primarily because of the inability to handle temporal variations (like the development of the morning valley flow circulation), spatial variations (wind shear in any direction), and the unknown effect of secondary circulations on the sigma σ parameters of plume size. Sometimes such models can be imbedded within more complex wind fields, but the approach should be used with caution, and better methodologies are now available.

TABLE 1A: GAUSSIAN PLUME MODELS

MODEL NAME	ORGANIZATION	REFERENCE
AIRDOS	Oak Ridge Ntl. Lab	Moore (1977)
AIRMOD	U.S. Army	Webster, et al. (1978)
APRAC2	E.P.A.	Ludwig and Obinata (1974)
AQSTM	Illinois EPA	Dickerson and Orphan (1975)
ARAC Gaussian	L.L.N.L.	
ATDL	NOAA/ATDL	Gifford (1973)
ATM	NOAA/ATDL	Patterson (1976)
COMRADEX-4	Rockwell Int.	Otter and Chung (1977)
DEPA	NOAA/ATDL	Rao (1981)
DIFOUT	Sandia Ntl. Lab.	Luna and Church (1969)
DNWND	Oak Ridge Ntl. Lab.	Fields and Miller (1980)
EDMS	RAS/NUC	Wilkie and Garry (1981)
GEM	Science Applications Inc.	Fabrick, Sklarew and Wilson (1977)
GLUMP II	MESOMET	Lyons, et al, (1981)
MESOPLUME	ER&T	Berkley and Bass (1979)
MIDAS	Pickard, Lowe and Garrick	Woodard (1975)
PAVAN	Battelle PNWL	Bander (1982)
RADOS	Dupont/SRL	Cooper
SNAGA	ER&T	-
SRDFM	NOAA/ARL	-
STRAM	Battelle PNWL	Hales, et al., (1977)
SUBDOSA	Battelle PNWL	Strenge, et al., (1976)
UNAMAP series (CDM, CRSTER, ISC, MPTER, PAL, PTDIS, PTMAX, PTMTP)	EPA	Turner (1979)
TEM	Texas Air Control Board	Christiansen (1976)
XOQDOQ	NRC	Sagendorf and Goll (1977)
3141	Enviroplan, Inc.	Ellis and Liu (197?)

TABLE 1B: GAUSSIAN IMPACT MODELS

CTDM	EPA	Strimaitis (1988)
COMPLEX I	EPA	EPA (1983)
COMPLEX II	EPA	EPA (1983)
RTDM	ER&T	Egan and Paine (1987)
VALLEY	EPA	Burt (1977)

Note: Table updated from Lewellen and Sykes (1985)

TABLE 2: GAUSSIAN PUFF AND PLUME SEGMENT MODELS

MODEL NAME	ORGANIZATION	REFERENCE
ADPLUM	Dupont/SRL	Huang (1980)
ASTRAP	ANL	Shannon (1981)
ATAD	NOAA/ARL	Heffter (1980)
AVACTA	AeroVironment	Chan and Tombach (1978)
AVPPM	Aerovironment	Zannetti (1980)
DRAX2	NOAA/ARL	Draxler (1979)
JEREMIAH	Dupont/SRL	Kern (1977)
MESODIF	NOAA/ARL	Start and Wendell (1974)
MESODIF-II	Battelle PNWL	Powell, et al., (1979)
MESOPUFF	ER&T	Benkley and Bass (1979)
MESOI	Battelle PNWL	Ramsdell and Athey (1981)
PFPL	Dupont/SRL	Garret and Murphy (1981)
PSM	TVA	Lott
RETADD	NOAA/ATDL	Begovich, et al., (1978)
REED	H.E. Cramer Co.	Bjorklund and Dumbauld (1978)
TRAGGY	Meteorologigcal Evaluation Service Inc.	Smith

TABLE 3: PHENOMENALOGICAL MODELS

GAUS PLUME MODEL FOR VALLEYS	Yankee Atmomic Electricity Massachussetts	Harvey and Hamawai (1986)
U. OF UTAH	Meteorology Department, U. of Utah	Lee and Kau (1984)
VALMET	Battelle PNWL	Whiteman and Allwine (1985)

Lewellen and Sykes (1985) calculate that the maximum range of applicability of such models can be related to the persistence of the wind. They suggest that the error expected in the average concentration over the period of persistence may be approximated by:

$$\text{Error} = \frac{(C_{\text{observed}} - C_{\text{calculated}})}{C_{\text{observed}}} = \left[\frac{\tau U}{x} - 1\right]^{-1}$$

where x is down-wind distance, U is wind speed, τ is persistence time, and provided $x/(U\tau) < 1$. Strong persistent winds are required to keep error from being large at distances beyond 10 km.

Vertical wind shear can often be the dominant factor in spreading a plume horizontally, since a turning of the wind with respect to altitude of 30° or more often occurs. Irwin (1979) attempted to incorporate vertical wind shear into a general algorithm for σ_y. The largest uncertainty in such dispersion models is likely to be caused by eddies in the size range of 1 to 10 km. Such eddies are responsible for uncertainty in position of the plume or the concentration level.

Many validations studies have been completed for Gaussian type models. It is generally accepted that the standard EPA type dispersion models are not reliable within a factor of two for prediction concentrations for characteristic dispersion conditions. Indeed both API and EPRI studies suggest model predictions and measured data for straightforward cases are often more than a factor of 5 apart at a majority of monitoring stations. Models generally agree with one-another better than they agree with field data. This suggests that there is little to choose between such models, and that a "natural" variation will exist in data which will always frustrate any effort to obtain better correlation. Bowne et al. (1983) found that gaussian plume models "showed no skill in predicting hour-by-hour concentrations at fixed receptors and exhibited only minimum skill in predicting the position and pattern of the plume foot-print." Such models seem to perform best when predicting maximum 1-hour, ground level concentration when specific time and location are not considered. This is definitely not adequate for specific drift calculations for forest sprays.

Gaussian Puff and Plume Segment Models which are derivatives of the simple Gaussian approach may alleviate the temporal and spatial problems identified above. Table 2 lists sixteen such models for use when unsteady nonhomogeneous wind field data are available. Such models may be imbedded in the more complex terrain models discussed in the following sections. One may logically expect a significant improvement in concentration predictions when strong horizontal meandering occurs; however, there are few validation studies available to specifically say "how much better" such techniques will be.

Unfortunately the puff models can not effectively react to wind variations which are on a smaller scale than the size of the puff or line segment. Whenever the resolution of the meteorological data is finer than the scale of the puff, errors will be induced in sigma σ, and when the resolution of the meteorological data is coarser than the scale of the puff, there will be a variance in the puff position. Some authors choose to use particle- or marker-in-cell methods to resolve this problem. Unfortunately such approaches often require up to 20,000 particles to resolve the plume and can be computer time intensive. SPLITPUFF was constructed in an attempt to solve these problems. The SPLITPUFF model permits puff combination or division as necessary to respond to important flow characteristics with 1/50 the number of parcels and 1/10 the computer time. Although some corrections are applied to the sigma σ values for temporal and spatial variations in meteorology, a puff-type approach is still unable to adjust

for dispersion effects due to secondary flows, back flow, or vertical wind shear.

B. Hill Intercept Models

EPA has several models in its UNAMAP series that can be used at sites where the height of the terrain exceeds the height of the stack -- VALLEY, COMPLEX I, , and COMPLEX II (See Table 1b). These models are essentially Gaussian plume models adjusted for plume height and surface variations by empirical and heuristic corrections. VALLEY is used as a worst-case screening model and assumes the plume always remains at the same elevation; although it may not indeed be a worst case model if recirculation can occur. Thus the models provide concentrations upon plume impact. The models are screening tools and were not based on field measurements. Field measurements by Start et al. (1975) in Huntigton Canyon, Utah, then revealed that dispersion in complex terrain exceeded that in flat terrain by as much as an order of magnitude. Thus plume impaction assumptions led to overly conservative predictions. Hanna et al. (1984) proposed a Gaussian model where plume path took into effect atmospheric stratification through a hill Froude number effects. More recently RTDM (Rough Terrain Dispersion Model) which uses ad hoc was tentatively approved by EPA for a "third level" screening model, and most recently the CTDM (Complex Terrain Diffusion Model) has been proposed which corrects for atmospheric stratification effects on plume paths around isolated hills and ridges (Hanna and Strimaitis, 1990). Unfortunately, these models are intended for plume impact on features closest to the source. They are not intended for application with many hills and valleys, nor do they contain any wake algorithms for simulating the mixing and recirculation found in cavity zones in the lee of a hill.

C. Phenomenological Models

Phenomenological models are those which use simple and specific insight about a limited phenomena to predict flow motions. For example Harvey and Hamawi (1986) modified the Gaussian dispersion equation to accommodate restricted lateral dispersion in deep river valleys. Multiple eddy reflections are assumed to occur between valley walls, the ground and the inversion over the valley; this leads to a simple imaging approach to estimating valley dispersion. Unfortunately the model presumes no temporal variation in valley conditions.

The boundary layer evolution of narrow mountain valleys during the early morning has been studied extensively, and a detailed description of this phenomena is provided by Whiteman (1990). Whiteman and Allwine (1985) and Bader and Whiteman (1989) proposed a phenomenological model titled VALMET for well-defined deep mountain valley diffusion based on the principles that:

> The nocturnal stable layer in a valley is destroyed by the growth of the convective boundary layer over the valley floor and sidewalls and the subsidence of the stable air mass in the valley center as the upslope motions transport mass out of the valley.
>
> Asymmetric heating of the valley sidewalls by the sun can skew the development of the boundary layer, with a tendency towards upslope motions on the heated sidewall and residual stability on the shaded sidewall.

The (1985) version of the model presumes that the valley air is "loaded" with pollution during the night, and then the early-morning motions fumigate this pollution downwards to the valley floor and sidewalls. The assumption is made that the night-time plume is "frozen" within the stable core. To work effectively twenty-seven input parameters are necessary to drive the model which

includes topographic, temperature inversion, downvalley wind speeds, atmospheric stability and sensible heat flux characteristics. The model is driven by thermodynamic equations for the convective boundary layer (cbl) ascent and inversion descent coupled with continuity relations to maintain mass conservation and calculate up-slope wind speeds.

The model has not been validated quantitatively against field measurements. It would require substantial revision to incorporate the segments of airplane delivered elevated aerosol clouds delivered over a range of valley locations. Finally, the model is limited to well-defined narrow valleys; thus, emission above or below the stable core, cross valley flows, tributary flows, etc. are not be accounted for in the VALMET model.

D. Mass Consistent or Objective Analysis Models

This class of models combines some objective (regression or maximizing or minimizing some variable) analysis of available wind data to form a wind field. The wind field analysis typically forces the resulting flow to satisfy air mass continuity by constraining the flow between the ground surface and some elevated inversion height. Such models may either produce a fully three-dimensional wind field, or they may solve the depth integrated continuity equation in a horizontal plane, and then recreate a vertical field assuming certain similarity profiles.

Table 4 lists objective analysis models which attempt to adjust wind fields rather than just interpolate between field data. Recognition of the need to include terrain effects in mass-consistent calculations led to the development of three-dimensional, time-independent, finite-difference, regional wind field models like MATHEW (Mass-Adjusted Three dimensional Wind field model) or FEMASS its finite element counterpart. In both models the Sasaki variational analysis technique is used in adjusting a discrete field of time-averaged interpolated winds for mass consistency. Basically, the procedure entails minimizing the squares of the differences of the observed (interpolate) and analyzed velocity components subject to the imposed constraint of incompressibility. MATHEW uses a traditional approach in simulating terrain by representing the boundary surface as a system of regular blocks whose impenetrable sides lie along coordinate lines. FEMASS produces the shape of the boundary surface by the lowest row of nodes in the grid which, when interconnected, form a system of curvilinear patches. Thus FEMASS produces a more precise representation of an irregular surface. NOABL is a modification of MATHEW to use a terrain-following coordinate system.

The atmosphere's thermal structure is not explicitly considered in the model equations of MATHEW or FEMASS, but the phenomenological effect of stability can be simulated to a certain extent by making a judicious choice of the Gauss precision moduli weights. The IMPACT model uses a series of "transparencies" which overlay the grid points and use a $1/r^4$ weighing of stability at the data points. IMPACT also treats thermal drainage winds by

TABLE 4: MASS CONSISTENT AND OBJECTIVE ANALYSIS MODELS

MODEL NAME	ORGANIZATION	REFERENCE
ATMOS1	Los Alamos Ntl. Lab.	Davis and Bunker (1980)
BLM/TM	NOAA/NWS	Long, Schaffer and Kemler (1978)
CHAPEAU	Dupont/SRL	Pepper and Baker (1979)
COMPLX	SRI International	Englich and Lee (1983)
FEMASS	LLNL	Gresho, et al., (1978)
IMPACT (Now called SMOG)	Form and Substance Inc.	Fabrick, et al., (1977) Wacker and Londergan (1984)
MASCON	LLNL	Dickerson (1978)
MATHEW/ADPIC	LLNL	Sherman, Lange (1978)
MESOGRID	ER&T	Morris, Berkley and Bass (1979)
NOABL	Science Applications Inc.	Phillips (1979)
PATRIC	LLNL	Lange (1978)
PHOENIX	Oak Ridge Ntl. Lab.	Murphy (1979)
PIC	Systems, Science & Software	Sklarew, et al, (1971)
RADM	Dames and Moore	Runchel, et al., (1979)
PDM	Systems Applications Inc.	Liu, et al, (1976)
TAPAS	USDA-Forest Service	Fox, et al., (1987)
(NUWNDS)		Ross, et al., (1988)
(NUATMOS)		"
U. of Hawaii BL Model	Meteorology Department U. of Hawaii	Erasmus (1984)

TABLE 5: PERTURBATION MODELS (LINEARIZED)

FLOWSTAR	Cambridge Environmental Services	Carruthers, et al., (1988)
MS3DJH/1,2,3,3R	Atmospheric Environment Service, Canada	Walmsley, et al., (1980 1982, 1986)

TABLE 6: DEPTH INTEGRATED MODELS

2D FLOW	--	Garrett and Smith (1984)
Integrated Drainage Model	NOAA/ATDL/ARL	Dobosy (1987)

adding a component to the vertical velocity near the surface, but the inclusion of thermally generated winds appears to be done without regard to local ground slope.

Mass consistent models have been modeled against mathematical tests, wind-tunnel terrain flows, and field data (Lewellen and Sykes, 1985; Lewellen, Sykes and Oliver, 1982). The block terrain feature in MATHEW induces O(1) errors near the surface, and yet with the exception of the layer immediately adjacent to terrain changes, the mass adjustment imposes relatively minor adjustments to the interpolated wind fields. Lewellen et al. (1982) question whether such minor changes justify the computer time spent on MATHEW. NOABL and FEMASS were found to produce substantial improvement in near surface wind predictions. NOABL seems unreliable when computing flows which go around obstacles, because the numerical scheme can diverge if the stability parameter is pushed too far in the direction of no vertical motion. IMPACT contains substantial numerical diffusion when flows move diagonally across the numerical grid. Many mass consistent models are not constructed to handle flow separation over ridges or valleys or temporal variations of wind data; however, modifications to include temporal effects should be possible. Finally objective models depend critically on the quality as well as quantity of the observed data and the empirically chosen constants involved in the models.

TAPAS (Topographic Air Pollution Analysis) is a computer modelling system being developed jointly by the Centre for Applied Mathematical Modeling at Chisholm Institute of Technology, Australia, and the Rocky Mountain Forest and Range Experiment Station, USDA-Forest Service. It contains simulation models of varying complexity, input data management routines, an on-line digital terrain data base, and graphical display procedures designed to assist non-computer oriented forrest service personnel. The TAPAS system currently uses wind-generation sub-modules called NUWNDS for low-cost two-dimensional screening and NUATMOS for a three-dimensional characterization of wind flow in complex terrain.

NUATMOS (version 5) is a highly improved version of the ATMOS1 code, which is now claimed to be completely stable, efficient and optimized to the extent that it will run on a PC-386 personal computer. NUATMOS employs terrain-following coordinates and variable vertical grid spacing. NUATMOS incorporates atmospheric stability effects via a characteristic Froude number to set the horizontal/vertical adjustment parameter α; hence, it is purported to account satisfactorily for terrain speed-up and even lee-wave behavior. The authors assert that it is the "most comprehensively tested and evaluated model of its type."

NUWND and NUATMOS have been compared against laboratory measurements of flow over isolated ridges and hills. They have also been compared against field data from the CTMD and ASCOT program. The model appears to correctly predict streamline splitting, plume impaction, and nocturnal drainage flows. The models have also been compared with data from four measurement sets from the Latrobe Valley, Australia. Surface winds were predicted with 50 to 70% reliability by the models.

Lee and Kau (1984) divided the flow over complex terrain into a drainage flow component, V_D, and a boundary layer component, V_B. The local drainage component was calculated from Prandtl's analytic solution which is a function of local slope, potential temperature surface to air differences, surface roughness, and height. The boundary layer component was derived from an analytic solution which includes geostrophic wind conditions, Monin-Obukhov stability length, surface roughness, and the Coriolis parameter. The resulting velocity field is then "adjusted" by an objective analysis until the flow is divergence free.

Predictions of the model were compared observations from the 1979 ASCOT experiment over the California Geysers area. One might consider this approach a "phenomenological" objective analysis method.

Another mass-consistent model which incorporates phenomenological arguments to adjust for surface roughness variation, cross-valley separation, ridge amplification and wind direction shear was developed by Erasmus (1986). The model was solved for grid spacing of only 100 m x 75 m over Kahuku Point, Oahu. The model presumes flow is dominated by mechanical rather than thermal processes; hence, it may not be suitable for early-morning forest spray applications.

E. Depth-Integrated Models

Integrated models have been applied to the atmospheric boundary layer for a number of years. Equations in horizontal parameter result from direct integration of the full primitive equations through the vertical. The resulting two-dimensional expressions may be solved for depth-averaged winds, temperatures, humidities, concentrations, etc. once entrainment relations are specified at the boundaries. They have been particularly popular for calculating cold-air drainage and winds over complex terrain in a terrain-following layer. Such models employ a two-dimensional horizontal grid. They work well over reasonably smooth terrain having resolvable features, but they can not handle ridge separation or deep, narrow valleys. A 2D FLOW model was prepared by Garrett and Smith (1984) which includes a Lagrangian particle diffusion model. Dobosy (1987) constructed a depth-integrated model which predicts night-time drainage flow in a trapezoidal shape valley. Conceptually any number of features including a main valley, its tributaries, sidewalls, head region and pooling region may be combined to form a representation of an entire drainage.

The Dobosy model has not been widely validated, does not predict local in-valley winds without presumptions about similarity, and is limited to night-time drainage situations; hence, it is probably inappropriate for the forest-spray program.

F. Linear or Perturbation Models

The equations of motion can be written in terms of flow perturbations induced by roughness, stratification, and terrain shape and linearized by eliminating higher order terms. Solutions for the effect of each disturbance can then be individually calculated and superimposed to determine the total wind field. A linear three-dimensional theory has been developed by Hunt, Leibovich and Richards (1988) (HLR) which is the foundation for the FLOWSTAR complex terrain model. The method of calculation is to compute Fourier transforms of the velocity field following HLR; then the transform is inverted numerically to calculate the actual flow variables at a point. In contrast to numerical models which solve the equations of motion on a grid, there is no iteration involved. Also the solution is determined explicitly once the algorithms and their assumptions have been agreed.

This solution approach is very appropriate for use on small personal computers. FLOWSTAR is currently configured to operate on PC-AT or 386 systems. Post processing graphic programs can produce a wide variety of streamline, flow vector, or profile graphs. The wind field can then be input into a puff dispersion model. A major advantage of the approach is that turbulence information is also predicted. The major limitations of the linearized analytical models are that they exclude large positive or negative changes in the mean flow and they exclude more complex models of turbulent shear stresses. Linear theories cannot describe large non-linear perturbations to the flow or

non-linear synergism where two or more effects combines such as roughness change and separation.

There are a number of conditions which must be satisfied in order for the model to give useful results:

i) the slopes of the terrain are small (typically less than 1/4),
ii) the changes in the natural logarithm of the roughness length, z_o, are small (less than 1.0),
iii) the profile of potential temperature can be approximated by a simple form,
iv) the upwind velocity profile increases from the ground upwards with no strong elevated shear layer,
v) the upwind conditions are varying slowly on a time scale compared to times required for a parcel to cross the calculation domain, and
vi) rapid hill-side heating or cooling does not occur.

The model will give results for flows where Fr > 1 and the terrain is gently rolling as opposed to deep narrow valleys.

The MS3DJH (Mason and Sykes 3-Dimensional version of the Jackson and Hunt's theory) series of models (MS3DJH/1, MS3DJH/2, MS3DJH/3, and MS3DJH/3R) are fully described in Walmsley et al. (1980, 1982, 1986). Again finite-area Fourier transform methods are used to obtain expressions for perturbation pressure, velocity and surface stress fields from the linearized equations of motion. These are evaluated numerically using discrete Fast Fourier Transforms. These models compare quite well when compared with more sophisticated models. Again the potential of the method is calculation of flow parameters over complex, three-dimensional terrain. Salmon et al. (1988) compare this method against field observations and laboratory simulations of flow over Kettle Hill, Alberta, Canada. Wind speeds and wind directions were closely predicted for neutral flow over this low hill. MS3DJH and FLOWSTAR can provide much higher resolution than other models currently available at a fraction of the computational cost.

G. Full Primitive Equation Models

Primitive equation models, meso-scale models, predictive models, meteorological models, or K-models compute all meteorological variables (wind, temperature, turbulence, mixed-layer height, etc.) given specification of initial conditions and domain boundary conditions. Boundary conditions of larger scale must always be specified, and small subgrid-scale processes must always be parameterized. Because of computational requirements, atmospheric models using fluid dynamics equations cannot span scales beyond a factor of 50 or so. Listed in the table below are the grid size and minimum and maximum phenomena length scales proposed by Kreitzberg, 1975.[1]

[1] In Table 7 the scale L_{min} should incorporate four grid intervals rather than two; since a two delta feature cannot be realistically represented.

TABLE 7: Atmospheric scales: model scope, characteristic length, and time scales (Kreitzberg, 1975).

	Model			Length	Time
Atmospheric scale	Grid (km)	L_{min} (km)	L_{max} (km)	$L \approx \lambda/4$ (km)	$T \approx P/4$
Regional	20	40	2000	20	3 hr
Mesoscale	1	2	100	10	1 hr
Local	0.08	0.16	8	1	15 min
Turbulent	0.01	0.02	1	0.2	1 min

Although Table 8 lists a few of the major primitive equation models used there are many other named and unnamed meso-scale model calculations which have been used to predict atmospheric flows ranging from mountain airflows, heat island flows, sea breezes, sudden roughness changes, etc. as shown in Table 9 extracted from Dickerson (1980). These models are quite complicated and require substantial computational resources. They contain many differences associated with computational molecules, grid systems, stability criteria, thermodynamics, boundary conditions, initial conditions, and turbulence models (closure assumptions). The closure assumptions lead to a hierarchy of turbulence models and often additional transport equations (K-models, Kϵ-models (2nd moment), sub-grid scale models (large eddy simulation or Deardorff models). Presently, atmospheric modelers utilize parameterizations of subgrid scale turbulence, cumulus cloud effects, radiative flux divergence, etc., based on an "average" parameterization. One might wonder how such an approach is compatible with the desire to produce "real time" local values.

Ross et al. (1988) state "Predictive models are, in general, time consuming and impractical for real-time applications." Most predictive modelers have a more optimistic belief that their models may eventually be useful for real time applications on small scales.[2] There are also questions concerning model verification. Many models have been found to include rather large numerical pseudo-viscosity (Havens and Schreurs, 1985). Concern about "inherent" flow variabilities has led to discussion like that of Praegle et al. (1990) which suggest that "chaos" does indeed limit many connectively dominated meso-scale flows. Alternatively recent results suggest that complex terrain flows may be dominated by linear forcing due to terrain boundary conditions, synoptic scale pressure fields, and local solar cycle. (This may explain why objective analysis models have worked quite well in complex terrain.)

Most experience with primitive equations exists for mesoscales where minimum grid size is 0.5 to 2 km or larger. These models have not been thoroughly compared with detailed meteorological data, but they can be said to

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[2] Pielke (1990) believes that current supercomputer workstation capabilities have sufficiently advanced and reduced in cost, that primitive equation models coupled via "nudging" with observations should be the modeling platform of choice for Forest Service spray drift predictions. He has documented over 50 studies which provide qualitative validation of primitive equation numerical model approach and more than 10 studies which provide quantitative agreement.

produce results which are "not counter-intuitive." Many well known phenomena are reproduced such as sea and land breeze cycles, lee waves, downslope and upslope winds, channeling, and valley drainage flow behavior. Less experience exists for smaller scale regions.

TABLE 8: MAJOR PRIMITIVE EQUATION MODELS

MODEL NAME	ORGANIZATION	REFERENCE
Argonne Model	Argonne Ntl. Lab. Los Alamos Ntl. Lab.	Yamada (1978)
ARAP	ARAP Inc.	Lewellen (1981)
CSU RAMS	Meteorology Department Colorado State University	Cotton, Pielke et al. (1982-90)
FEM-3	LLNL	Chan (1988)
HOTMAC	Yamada Science & Art Co.	Yamada (1989)
Penn State Model	Penn State and NCAR	Anthes and Warner (1978)
SIGMET	Science Applications Inc.	Davis and Freeman (1981)
TEMPEST	Battelle PNWL	Trent, et al., (1983)
UK Met Office Mesoscale Model	UK Meteorological Office	Tapp and White (1976)

TABLE 9: DICKERSON (1980)

Models that may be used to simulate airflow over a complex terrain area. Models are grouped according to main subject to which they have been applied: mountain airflow, heat island, sea breeze, or sudden roughness change.

* Includes topography

K MODEL

Mountain Airflow

Anthes & Warner 1974*
Fosberg 1967, 1969*
Jacobs & Pandolfo 1974*
Klemp & Liffy 1978*
Mahrer & Pielke 1975*
Mason & Sykes 1978*
Nickerson & Magaziner 1976*
Taylor 1977*

Heat Island

Bornstein 1975
Delage & Taylor 1970
Estoque & Bhumralkar 1969
Estoque & Bhumralkar 1970
Gulman & Torrance 1975
Mahrer & Pielke 1976
Ochs 1975 (Ref. 87)
Pielke & Mahrer 1975
Yu & Wagner 1975

Sea breeze

Estoque 1961
Estoque 1962
Fisher 1961
Magata 1965
McPherson 1970
Moroz 1967
Neumann & Mahrer 1974
Pielke 1974
Tapp & White 1976

Sudden roughness change

Huang & Nickerson 1974
Taylor 1969

CLOSURE MODEL

Mountain Airflow

Benque & Dewagenaere 1977*
Rao et al. (1974)
Yamada 1978*

DEARDORFF'S MODEL

Deardorff 1974

Very few cases are available where a full primitive model calculation is compared to a well-documented terrain flow. In a draft paper prepared by Dawson, Stock and Lamb (1990) the TEMPEST code was used to solve for flow over Steptoe Butte, Washington. The code used a $k\epsilon$-turbulence model, grid cell dimensions as small as 116 m by 175 m by 16 m, but a rather crude approximation to hill shape. Inaccuracy due to false diffusion was found to be quite significant (1 to 3 times as great as turbulent mass diffusivities in the recirculation and wake regions of the hill).

V. CONCLUSIONS AND RECOMMENDATIONS

The randomness inherent in atmospheric turbulence imposes a natural limit on flow predictability, which provides an upper bound on model accuracy as a function of available data. Under certain strongly convective conditions, even a perfect simulation of the mean flow and turbulence can provide a poor estimate of concentration distributions observed. Nonetheless, recent analysis suggests that some degree of stratification may be obtained in flows strongly influenced by local boundary shapes, strong wind fields, or the diurnal cycle.

Given the desire to use the "best available" science and numerical models in the forest spray program limited by the desire to use "off-the-shelf" codes, a selection among the models reviewed can be made. Computational models most suitable for adoption by the forest spray program are:

TAPAS (NUATMOS) - This model is attractive because it is a) oriented toward forest and land-management personnel, b) contains attractive input and output modules, and c) can operate quickly on mini or micro computers.

The model should predict flow over undulating or rolling terrain in situations where drainage movements are small, ridge separation does not occur, and winds are moderate or high.

FLOWSTAR - This model is also attractive because it is a) fully documented, b) input and output modules could be modified to fit forest service needs, and c) can operate on mini or micro computers.

The model can provide almost infinite resolution over undulating or rolling terrain in situations where drainage movements are absent, ridge separation does not occur, and winds are moderate or high.

VALMET - This model is attractive because it a) inherently handles temporal variations of valley flows, and b) can operate on mini size computer systems.

The model can predict night-time and early-morning flow behavior in narrow valleys of simple planform where strong synoptic flows are absent. The model will require extensive development before it can include cross-valley flows and tributary flows.

SUMMARY OF ADVANTAGES AND DISADVANTAGES OF VARIOUS MODEL CLASSIFICATIONS:

Gaussian Plume Models:

Advantages

1. Programmable on small micro computer systems for very fast execution,
2. A number of scenarios can be quickly run to assist planning,
3. Minimal meteorological data required, and
4. Predicts maximum hourly concentrations well when time and space variations are not critical.

Disadvantages

1. Validations show models do not predict hourly observations at a specific time and location beyond the immediate vicinity of the release,
2. Models can not track changing meteorological conditions such as lead to fumigation in valley flows,
3. Cannot treat spatial inhomogeneities like wind shear or terrain specific features,
4. Requires an empirical specification of sigmas versus stability and distance, and
5. Does not provide any estimate of variance from predicted values.

Gaussian Puff Models:

Advantages

1. Can be implemented on local minicomputers,
2. Can track changing wind and stability, and
3. Accuracy is limited only by resolution of meteorological data and the scale of the tracked puffs.

Disadvantages

1. Requires significant local wind data,
2. Models do not generally treat dispersion augmentation due to wind shear,
3. Requires an empirical specification of sigmas versus stability and distance, and
4. Does not provide any estimate of variance from predicted values.

Phenomenological Models:

Advantages

1. Models are designed to reproduce specifically the dominant features of the identified flow system,
2. Models like VALMET can inherently handle complicated temporal variations of valley flows, and
3. Recent versions of the model can operate on mini size computers.

Disadvantages

1. Models are limited to terrain geometries for which they were created (e.g. VALMET is limited to narrow valleys of simple planform),

2. Models usually can not handle flow systems beyond their design range (e.g. cross-valley flows, tributary flows, sudden change in terrain shape or direction), and
3. Models will require extensive development to make them more flexible.

Mass Consistent Objective Analysis Models:

Advantages

1. Models can be terrain specific and provide for terrain steering of winds,
2. Models can handle wind shear,
3. Versions of these models can handle stratification, surface roughness and lee wave behavior, and.
4. Recent versions of the model can operate on mini or micro computers.

Disadvantages

1. Requires substantial input data to yield accurate results (results are possible with minimal input, but accuracy degrades),
2. Turbulent diffusion parameters such as sigmas must be determined separately,
3. Models can not handle flow separation or strong drainage flows, and
4. Does not provide any estimate of variance from predicted values.

Depth Integrated Models:

Advantages

1. Grid reduction by depth integration increases substantially the computer space available for horizontal domain size or horizontal resolution; hence, large domains can be examined on mini or micro size computers, and
2. Models have been extensively validated against oceanographic and atmospheric flows as well as heavy gas spills.

Disadvantages

1. Models can not handle flow separation, strong vertical shear, or recirculation situations, and
2. Models are effectively limited to situations where inversions or other boundaries cap the layer being examined.

Linear or Perturbation Models:

Advantages

1. Models can be terrain specific and provide for terrain steering of winds,
2. Models can provide almost infinite resolution over the domain chosen,
3. Models can adjust for atmospheric stratification, wind shear, and inhomogeneities in surface roughness, and
4. Models can operate on mini or micro computers.

Disadvantages

1. Requires substantial input data to yield accurate results (results are possible with minimal input, but accuracy degrades),
2. Turbulent diffusion parameters such as sigmas must be determined separately,
3. Models can not handle flow separation or strong drainage flows, and
4. Models do not provide any estimate of variance from predicted values.

Primitive Equation Models:

Advantages

1. Models can provide simulations of almost all meteorological variables,
2. Models contain all the necessary physics to predict wind shear, flow separation, secondary flows, etc., and
3. Models can be structured to take advantage of almost all of available data in providing a best-guess simulation.

Disadvantages

1. Models require very large computing resources,
2. Further development work will be required to reduce response time and make input and output modules user friendly,
3. Boundary condition data may often be difficult to obtain,
4. Some tests suggest many models contain large numerical pseudo-viscosity which distorts the predictions, and
5. Many of these models are still not very well validated.

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Appendix C

DRAFT 5-22-90

Discussion of Desired Modeled Output for a Combined FSCBG/COMPLEX Terrain Model

by

John W. Barry

The FSCBG aerial spray model is used to plan, conduct, and evaluate field experiments and control projects. It is a powerful tool for planning and designing field operations, helping to insure safe and economical application of biologicals, chemicals, fertilizers and other wet and dry materials. The model allows the evaluation of a wide range of variables and combination of variables inexpensively, at the computer, in lieu of costly field testing. Variables can be controlled thus negating the need for field tests. This conserves human and material resources, and reduces environmental insult that may result from field testing. Expressed in other terms the FSCBG model can be used to search out that combination of variables (weather, equipment, and agent) that has the greatest probability of achieving the desired result. The need might simply be an even application of fertilizer over flat terrain or the distribution of a naturally occurring biological in a forest canopy over complex terrain to control an introduced defoliating insect. We have unsuccessfully applied pesticides many times to forests under variables that the model could have clearly demonstrated or predicted would have been unsuccessful in meeting project objectives. Likewise the model can be used to signal problems during operational projects and explain both successes and failures during project reviews.

The current version of FSCBG (3.5) makes predictions of spray deposition and airborne concentrations of gases and particulates over flat, open or forested terrain. It does not have the capability of making these predictions in complex terrain. We have need tp predict deposition and airborne concentration in all types of forested terrain which more often than not is in complex terrain. To achieve this we plan to couple FSCBG to an existing complex terrain model.

We are interested eventually in achieving a total mass accountancy of materials that are released as elevated line sources from either airborne or ground platforms. Achieving this would necessitate coupling FSCBG to both a complex terrain model and a larger scale air shed model. To illustrate the complex terrain model might encompass air flow from a treatment site to the first drainage, along other secondary drainages, then to the primary drainage - perhaps a distance up to 10 miles. In such a scenario we would be dealing with drift associated with local, diurnal, down-slope winds and would be interested in tracking the plume until up-slope winds become established. This will not, however, provide us a total mass accountancy.

For mass accountancy we would also need an air shed model that tracks the plume as it is influenced by diurnal changes in atmospheric conditions. These conditions change dramatically as the sun heats the surface and changes the valley air mass. The gases and particulates move up-slope over ridges, and expand laterally while difusing upward to the mixing layer. We recognize a need for this capability; however the first step in achieving total accountancy is coupling a complex terrain model to FSCBG. The scope of this report is limited to the latter and to predicting deposition and airborne concentrations

downwind under inversion through lapse conditions to the beginning of up-slope winds.

FSCBG predicts deposition and airborne concentration as a function of:

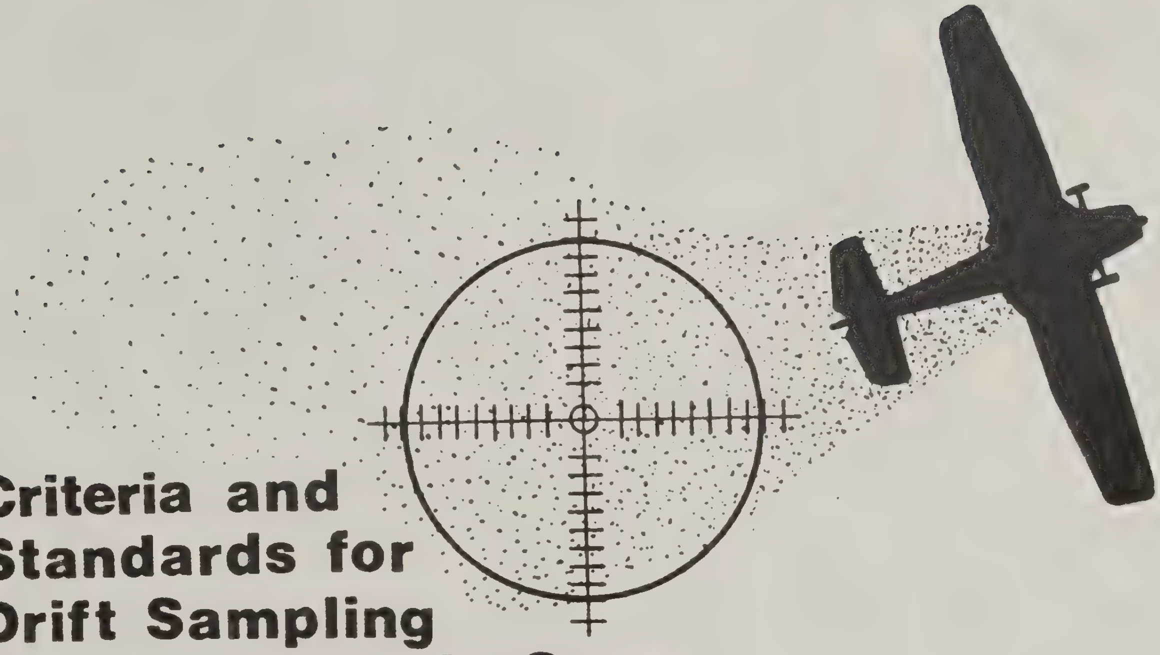
- Atmospheric conditions
    - Wind
    - Temperature
    - Relative humidity
    - Barometric pressure
- Agent Characteristics
    - Specific gravity
    - Particle or drop size
    - Volatile component and fraction
- Application parameters
    - Physical description of spray platform
    - Position of output orifices
    - Release height
    - Application volume
    - Track (x,y) of spray platform
- Canopy description
    - Height
    - Stem spacing
    - Foliage density
    - Leaf geometry

As indicated FSCBG predicts the deposition and air concentration of the applied agent. Deposition is that part of the applied agent that deposits on any surface within or outside the treatment area. The model predicts within tree and crop canopies and on open ground surfaces. The predictions are in drops or particles per unit area (e.g., drops per square centimeters); mass (e.g., milligrams per square meter); or volume (e.g., gallons per acre). Predictions are needed for downwind distances up to 10 miles.

Air concentration is that part of the applied agent cloud that at any point in time is airborne in the form of vapor, drops, and particles. Air concentration is predicted in terms of volume/mass e.g., milligrams per cubic feet. This can be in peak concentration, total concentration, total dose, or dosage. For human risk exposure predictions and studies total dose and dosage are needed. Dose is the total amount a person would breathe while exposed to the agent. Dosage would be the amount integrated over time that a person might breath and would be expressed e.g., milligrams per second. Predictions are needed for downwind distances up to 15 miles.

The requirement is for model outputs to be presented three dimensionally, that is at x,y,z points, over any combination of complex and flat terrain covered with crops, forests or other plants, or barren of vegetation. This will require adoption of a geographical information system and supporting software and hardware.

Appendix D



Criteria and Standards for Drift Sampling Forest Pesticide Spray

ED & T 2353
SPRAY DEPOSIT ASSESSMENT

OCTOBER 1977

USDA ■ Forest Service Equipment Development Center ■ Missoula, Montana

7752 2218

PROJECT RECORD

CRITERIA AND STANDARDS FOR DRIFT SAMPLING FOREST PESTICIDE SPRAY

ED&T 2353

Spray Deposit Assessment

By

ROBERT EKBLAD

MECHANICAL ENGINEER

October 1977

Forest Service - U. S. Department of Agriculture
Equipment Development Center
Missoula, Montana 59801

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ABSTRACT

The Equipment Development Center at Missoula (MEDC) has been asked to evaluate sampling devices and develop a standard sampler (or samplers) to detect and measure significant amounts of pesticides that drift outside the target during aerial applications over forest terrain.

This preliminary report summarizes the principles of drift sampling and recommends criteria for selecting samplers and standards for reporting drift that will be sent to those concerned with drift information. Comments on these recommended criteria are solicited to allow us to establish uniform standards for sampling and reporting drift and to allow us to develop a standard sampler (or samplers).

A report on Equipment Development and Test Project 2353, Spray Deposit Assessment Systems, funded by the Forest Insect and Disease Management Staff.

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INTRODUCTION

The Equipment Development Center (MEDC) at Missoula, Montana, has been asked to provide a standard sampler (or samplers) to detect and measure significant amounts of pesticides that have drifted outside a target area during aerial applications over complex forest terrain.

This is a preliminary report on that work. It summarizes the principles of drift sampling and recommends criteria and standards for sampling drift. This report will be sent to a diverse group concerned with collecting, analyzing, or using drift information to solicit their comments on the recommended criteria. These comments will allow us to establish uniform standards for sampling and reporting drift, which is a necessary first step before we can evaluate existing sampling devices and develop and implement a standard sampler (or samplers) for Forest Service use.

BACKGROUND

Applying sprays aerially inevitably produces very small droplets that drift outside the target, and under adverse conditions even droplets that would normally settle within the target will move outside the target area. Detecting pesticides outside the target area helps evaluate environmental damage as well as compare spray systems and compare mixes, validate drift models, and develop environmental policies.

Accounting for the fate of all the spray material would be an enormous task. Figure 1 is an adaptation of a diagrammatic model (Southwell 1974) used to subjectively describe the fate of pesticide spray. MEDC is concerned with the coarse aerosol carried off target by the surface wind before spray is deposited downwind on soil, plants, water, or animals (heavy outline in figure 1).

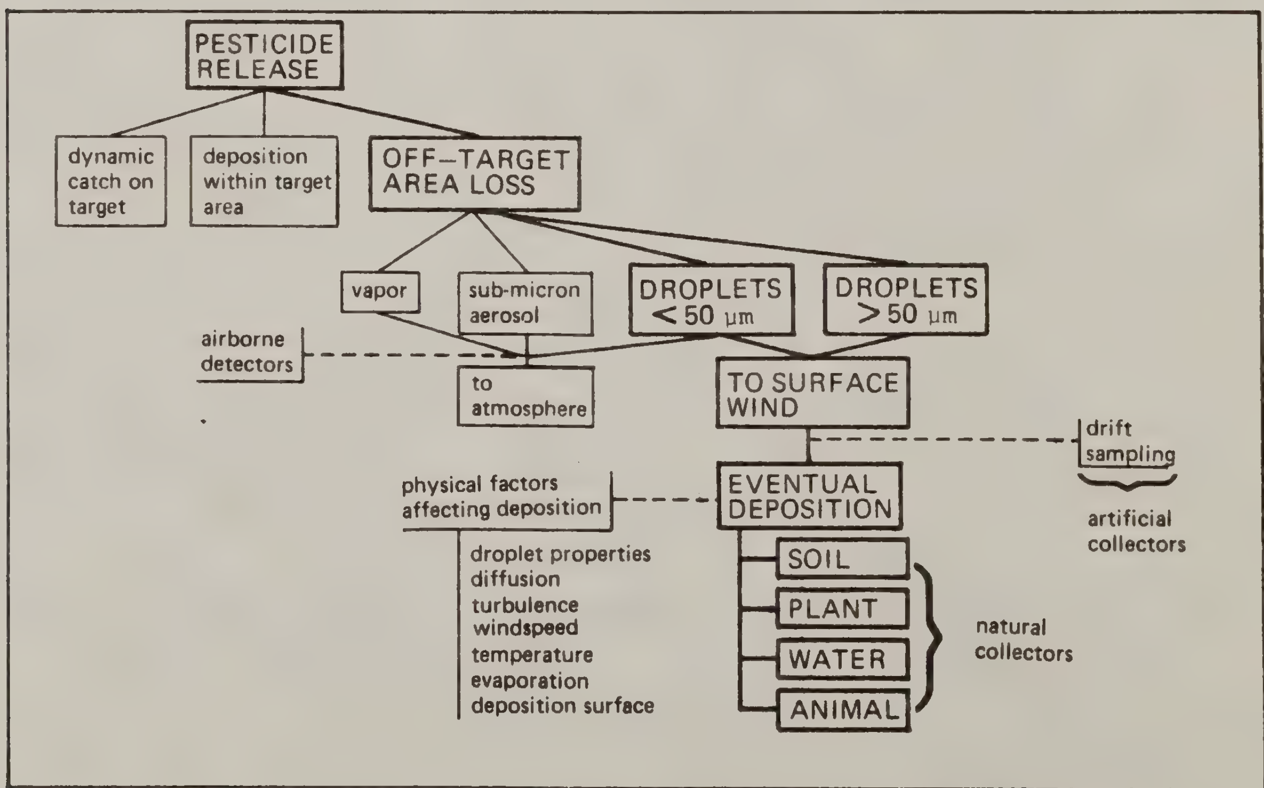

Figure 1.--Diagram of pesticide travel and scope of drift sampling (heavy outline).

Measuring drift into nontarget forest spray areas has been accomplished in two ways on pilot and operational projects: Droplets falling on ground deposition cards have been collected and some air sampling has been done on an experimental basis in a forest by Barry (1974) and Bergen (1976).

Nonforest tests have been conducted with spray aircraft flying over deposit card lines placed on the ground under favorable meteorological conditions. Spray release was extended considerably beyond the card line to insure capturing small droplets with shallow trajectories. Mass recovery varied between 15 and 55 percent (Dumbauld and Rafferty 1976 ; Orchard and others 1974). Even allowing for errors in methods, these tests show that a substantial portion of the spray cloud may evaporate or continue to drift beyond the target area. The airborne droplets are of course subject to impaction and impingement on foliage before leaving the target area. Therefore obstacles such as branches and leaves in the drift zone would scavenge a portion of the droplets.

A variety of aerosol and particulate sampling devices developed for air pollution studies, public health, spore transport, and chemical and biological warfare have been adapted for sampling drift of forest and agricultural chemicals. No uniform method of reporting results and no primary reference standards for sampling spray drift have been established for either forest or agricultural spraying. Even in public health and air pollution studies where standards for sampling and reporting results have been established, there is no unbiased standard sampler to collect and measure the particulate or droplets.

MEDC will limit its search for a standard sampler to artificial collectors in surface winds, which measure the amount of material available for deposition at a point or beyond that point.

There is of course merit and need for measuring deposits on natural collectors and testing should be pursued by those scientists concerned with water, soil, or a particular organism.

Even after a successful standard sampler (or samplers) has been developed, efforts should continue to establish relationships between deposits on artificial collectors and deposits on natural collectors to allow us to evaluate effects of drift.

Every sampler has limitations. Objectives of the investigator are of primary importance in selecting the most suitable sampler. Defining sampling objectives should narrow the scope of development and evaluation to manageable proportions.

Potential uses of drift samplers in conjunction with spraying forest pesticides include:

1. Detect pesticides in control (nonspray) blocks.

2. Detect presence and amount of pesticides in sensitive areas containing water, birds, insects, fish, wild and domestic mammals, bees, farmsteads, and recreation areas, and concentrations of people.

3. Provide data base for predicting drift.

4. Compare drift from different spray systems or tank mixes.

5. Define meteorological conditions that will minimize drift.

6. Provide information for future environmental analysis.

7. Provide data to defend against allegations of damage.

8. Validate drift models.

9. Develop environmental policies.

10. Provide data for improvement of future spray operations.

PURPOSE AND SCOPE OF DRIFT SAMPLING

After the amount and extent of drift have been measured, it is useful to predict the relationship between deposits on artificial collectors and deposits on natural collectors. This can be done in two ways:

1. By applying equations for atmospheric transport and diffusion and physics of particle behavior. A well developed body of knowledge is available for specific targets and conditions.

2. By comparing statistical correlations between deposits measured on artificial collectors and those on natural collectors with other parameters such as the stability ratio. Results of comparing these relationships in agricultural and forest spraying have been reported by Armstrong (1975) and Yates and Akesson (1975).

Choosing the most effective sampler depends on a clear understanding of the principles of drift sampling. When a pollutant is introduced into the atmosphere, its transport is influenced by how it is released and the nature of the atmosphere, particularly the air movement. Except for a few special cases, the farther downwind the cloud travels, the more dispersed the pollutant becomes.

Equations predicting diffusion were made as early as 1855 based on molecular agitation. Later equations incorporated the effect of turbulent eddies. Equations developed by Cramer and others (1972) as well as other investigators incorporated the effect of gravity on particles of significant size. All these equations are extremely complex, but are available in meteorological source materials.

Common Forms for Reporting Drift

Determining drift depends not only on complex mathematical computations but on the source of pollutant as well. Common classifications of sources for measuring pollutants are:

SOURCE	EXAMPLE
Continuous Point	Plume from smoke stack
Continuous Line	Busy Highway
Continuous Area	City
Instantaneous Point	Explosion
Instantaneous Line	Single swath of spray aircraft

If the amount and size distribution of a pollutant, as well as airspeed and air density, are measured and recorded continuously, the data may be presented in several ways. If all parameters are known, data can be converted from one form to another, in addition to the simple conversion from English to metric units. However, because it is seldom practical or economical to measure and record all the parameters, in practice the terms cannot be readily converted from one expression to another. It is important to establish how to present the data, since a different kind of sampler may be needed to measure each form. For example, a sampler suitable for measuring dosage may not be suitable for measuring flux (table 1).

The volume, number of particles, or mass of particles are sometimes reported by several categories of droplet size rather than the total number of particles, volume, or mass.

Each of these terms is appropriate for some applications and each describes a significant physical property. A clear understanding of each term is essential to understanding the significance of the reporting standard.

Definition of Terms

Concentration - Concentration is the amount of aerosol contained in a unit volume of air (fig. 2). It is usually

Table 1.--*Standard terms for reporting presence of aerosols or particulates*

TERM	SYMBOL	UNITS	COMMENTS
Concentration	$\frac{\mu g}{m^3}$	$\frac{\text{microgram}}{\text{meter}^3}$	
Dosage	$\frac{\mu g.sec}{m^3}$	$\frac{\text{microgram second}}{\text{meter}^3}$	
Flux	$\frac{\mu g}{m^2.sec}$	$\frac{\text{microgram}}{\text{meter}^2\ \text{second}}$	usually vertical
Total flux	$\frac{\mu g}{m^2}$	$\frac{\text{microgram}}{\text{meter}^2}$	usually vertical
Parts per million	ppm		nondimensional volume ratio
Deposit	$\frac{\mu g}{m^2}$	$\frac{\text{microgram}}{\text{meter}^2}$	usually horizontal
Droplet deposit density	$\frac{\text{drops}}{cm^2}$	$\frac{\text{drops}}{\text{centimeter}^2}$	

given as micrograms (μg) per cubic meter (m^3). The volume of air may be stationary or moving, but unless the windspeed is known, the concentration cannot be used to compute the total aerosol moving past a given point. Concentration is useful for setting standards for inhaled aerosols. Inhalation takes place at a fixed rate, independent of windspeed or total aerosol passing a given point.

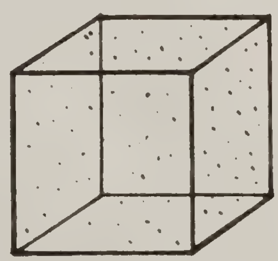

Figure 2.--Concentration - Mass or volume of aerosol in a given volume of air.

If an aerosol is injected at a fixed rate into moving air, the concentration will vary inversely with the windspeed. This is illustrated in figure 3 with a smoke plume at two windspeeds. On the other hand, if an aerosol is already present and the air velocity is suddenly increased by flowing through a reduced cross section of a duct or being channeled through a narrow canyon, the concentration should remain nearly constant.

It is difficult to measure concentration from an instantaneous source since the

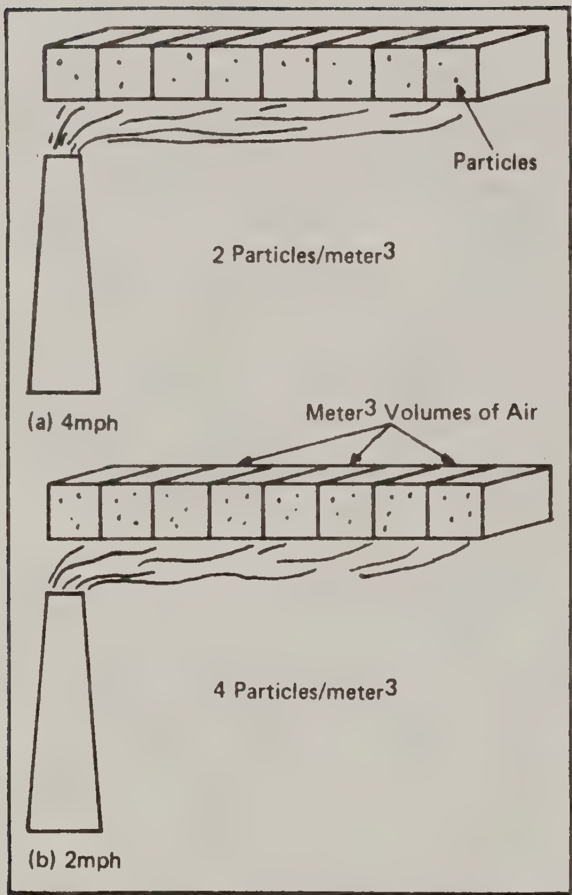

Figure 3.--Effect of wind speed on concentration from a point source without cloud expansion.

concentration varies near the source from zero to peak and back to zero in a short time. At long downwind distances, when a cloud is more diffuse in the alongwind direction, the time required for cloud passage increases and variations in concentration are not as rapid. Normally the exact time the aerosol is present is not known. A technique known as grab sampling has been used to overcome this problem. Grab sampling consists of quickly capturing a volume of air by some means such as a balloon or pump and analyzing it, usually in a laboratory. Several samples would have to be taken at intervals to establish the variation of concentration.

Dosage - The physical significance of dosage is summation of concentration with respect to time. If the concentration is constant, dosage is simply the product of concentration and time. Otherwise, dosage is the area under the curve when concentration is plotted against time. Figure 4 illustrates this concept for two types of sources. The units for dosage are $\mu g.sec/m^3$.

In practice dosage is usually determined by dividing the total weight of the aerosol sample by the sampling rate.

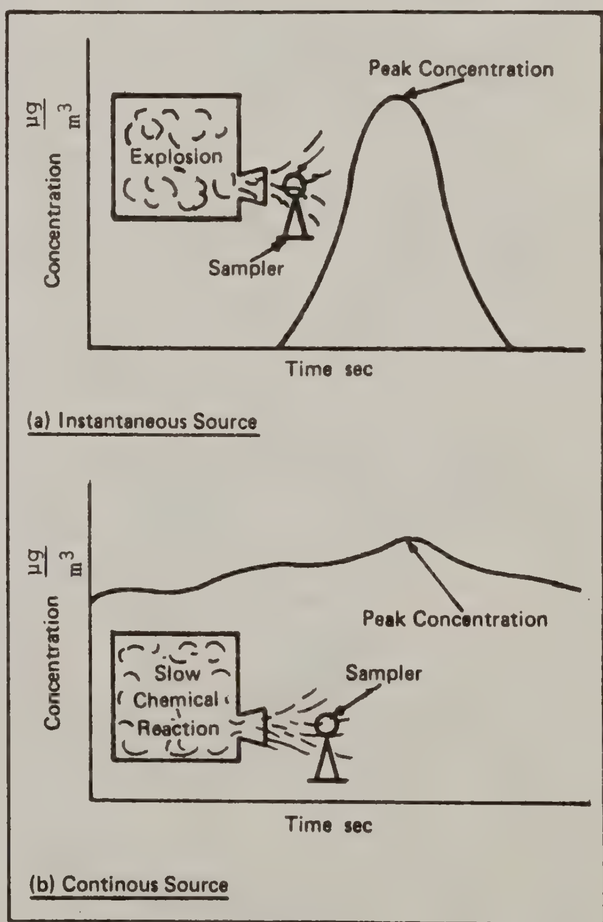

Figure 4.--Variation of concentration from two types of sources.

Dosage is frequently used in public health standards to set limits when low concentrations over a long period of time are harmful.

Flux - Flux in many physical sciences denotes rate of passage of energy or substance per unit area. For an aerosol it would be weight of aerosol per unit area per second $\mu g/m^2.sec$. Figure 5 depicts a large fixed reference volume through which a spray cloud is passing. Imagine a 1 square meter window at the bottom of the cube at ground level and another window of the same size on the leeward side of the cube. If the spray cube contains a range of droplet sizes, some will settle or deposit through the horizontal window. The droplets that pass through the vertical window are representative of the airborne portion of the cloud. The flux would represent the weight of aerosol passing through the 1 square meter window in 1 second.

Total Flux - By summing all flux over a period of time, total flux in $\mu g/m^2$ can be measured. In the case of an instantaneous source, total flux represents the total material passing through the imaginary vertical window. It can be given in the same units used for deposition on horizontal cards.

Parts per million (ppm) - The amount of a pollutant is sometimes expressed as ppm, the number of pollutant molecules per million molecules of air. This is concentration by volume and can be converted to mass concentration by suitable formula. Since ppm is a measure of concentration, it does not indicate total material passing a given point unless airspeed and density are known.

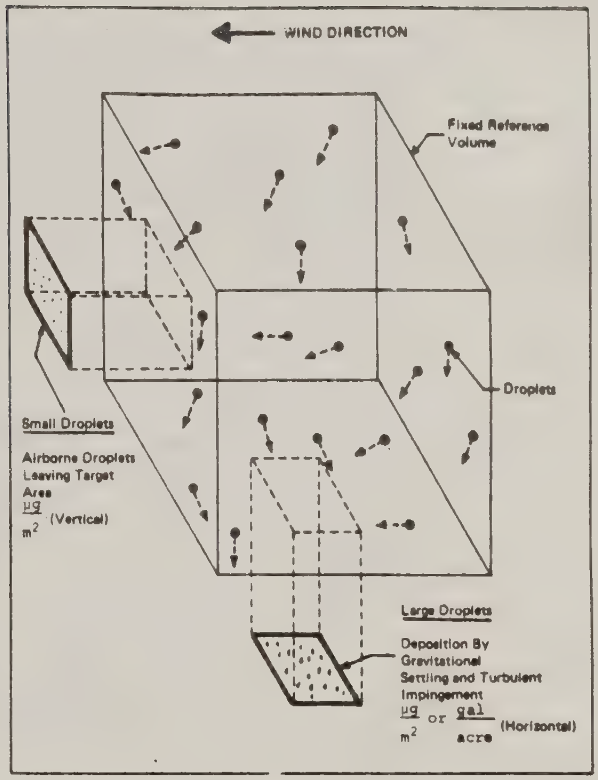

Figure 5.--Comparison of vertical flux and horizontal deposit.

Deposit - Deposit is usually associated with gravity samplers. Samplers collect droplets that have significant gravitation settling velocity and, in the presence of turbulent air, smaller droplets that are impinged on the sampler. The units may be $\mu g/m^2$ but are usually given in gallon or ounces per acre. These units can be directly compared to the units of total flux.

All of the above terms, with the exception of ppm, are expressions of weight. The same concepts can be used to express volume of aerosol or numbers of particles or droplets.

Pesticide and herbicide drift studies have been reported using all these terms: dosage, concentration, and deposit (Murray and Vaughan 1969); concentration (Ware and others 1972); dosage and deposit (Barry and others 1974); and total flux and deposit (Yates and Akesson 1975).

DRIFT SAMPLERS

There are many commercial and homemade sampling devices, ranging from extremely simple inexpensive devices to highly sophisticated expensive devices. Each has shortcomings and our preliminary investigation has not shown any one sampler to be obviously most suited for our objective of sampling aerosol carried off target by surface winds before it is deposited on soil, plants, water, or animals (heavy outline fig. 1). Further evaluation or modification of samplers must compare their performance.

Following is a list of criteria for evaluating samplers in order of decreasing importance. The first six items are most important.

Evaluation Criteria

Sampler should be:

1. Useful for intended application
2. Evaluation must consider cost factors:
   - Initial cost
   - Cost to deploy and operate
   - Cost to analyze
3. Rugged and operable in field environment
4. Readily portable
5. Capable of being balloon supported up to 150 feet
6. Simple to operate
7. Suitable for remote control
8. Battery powered or not require power
9. Independent of tracer in spray
10. Have proven performance
11. Available for 1978 field season
12. Suitable for quick and dirty approximation in field
13. Suitable for analysis without extensive lab facilities

Samplers to be Evaluated

The common methods used for aerosol sampling operate on a few basic principles. MEDC will review the specific sampling devices and evaluate their performance.

Basic types of samplers available are:

Gravitational settling

Impaction

Suction

Grab sampling

Exotic

Samplers to be considered in MEDC evaluation are:

Gravitational Settling - Horizontal surfaces have been used extensively for collecting airborne pollutants. Large droplets settle at their terminal velocity and are retained on the surface. For smaller droplets, deposition is a function of windspeed, turbulence, droplet size, concentration, and possibly other undefined factors. This makes it difficult to obtain reproducible results for smaller droplets whose terminal velocity approaches the

turbulent eddy velocity. For larger droplets these samplers are fairly reliable.

Impaction - The most common impaction sampler is a horizontal or vertical cylinder. Droplets approaching the cylinder are impacted upon the surface. However, based on droplet size and cylinder size, some droplets will be deflected around the sampler. If the windspeed is known, calculations can correct for collection efficiency. By using a variety of sizes and position of cylinders a collection efficiency can also be made without knowing windspeed. One of the principal disadvantages of the device is its low sampling rate at low windspeeds.

Another version of the impaction sampler, which is useful even in still air, is the rotating impactor. It may be a small bar, microscope slide, or cylinder that is rotated about an axis parallel to but not coincidental with its own axis. High rotational speed essentially masks the normal windspeed and can give a high collection efficiency for even small droplets. If it is a constant speed device, it will also have a fixed sampling rate. A rather subtle but important shortcoming is that it cannot be used to measure total flux unless the windspeed is known. Results are usually presented as dosage. It is expected that a region of turbulence will surround the sampling surface, making it difficult to apply collection efficiency equations based on laminar flow. Therefore they are usually calibrated for each particle or droplet size. With larger droplets and heavy loading, centrifugal detachment and reentrainment may be experienced.

Suction - A more sophisticated group of samplers is based on the principle of drawing air into an entrance with a pump and causing the droplets or particles to impinge, impact, or settle on some internal sampling surface. All of these devices require external power. High volume samplers commonly used for air pollution studies require a gasoline engine, high amperage batteries or alternating current to power the vacuum pump. Commercial units small enough to be worn on the lapel and battery powered are also available. However, they will have lower sampling rates and require a more sensitive analytic assessment technique.

To obtain an isokinetic sample the entrance must face directly into the wind and have the same entrance velocity as the mean windspeed. This can seldom be achieved in practice, so a bias due to anisokinetic sampling must be expected. Total flux cannot be measured unless windspeed is known.

Grab Sampling - It is principally useful for measuring concentration which may be expected to vary with time. Grab sampling is accomplished by quickly capturing a volume of air in some sort of pump and returning it to a laboratory for analysis.

Exotic - Other systems of tracking and measuring aerosols are in use. Some of these are light scatter, lidar tracking, and radar tracking. Most appear to be principally laboratory or research devices and are too bulky or expensive for routine forest use.

DISCUSSION

It is important to establish standard methods and uniform units for reporting drift if sampler performance is to be compared and results of drift sampling are to be biologically useful.

Aerial spraying is usually done during a short period of time with interruptions from loading or equipment failure. Therefore, it seems reasonable to consider the source an instantaneous line source, which means that there will be wide fluctuations in downwind concentration depending on downwind distance and the alongwind extent of the cloud. To measure actual levels of concentration would require grab sampling or some similar technique. Although dosage is useful if you want to know assimilation at a fixed rate of respiration, total flux, which indicates the amount of material available for deposit on travel downwind, appears to be the most useful form for our objective.

Selection of droplet size range will also influence selection of a sampler. Dennis (1976) defines coarse aerosol from 10 to 40 μm. This classification is also defined as fog. Mist is defined as droplets produced by atomization or condensation processes and larger than 40 μm. Since we may be concerned with drift over short distances, the upper limit of the range might be extended to at least 50 μm. Most samplers are not suitable for collecting a wide range of droplet size with reasonable efficiency. With this in mind, a lower limit for droplet size of 15 μm and an upper limit of 50 μm may be a reasonable selection.

The minimum detection level in terms of total flux or concentration is also important in selecting a sampler. One 20 μm drop per square centimeter is equivalent to 4.2×10^{-9} gram per square centimeter or 0.418 gram per hectare or an average concentration of 1.3×10^{-11} gram per liter for 1 hour of sampling in a 2 mph wind. Yates and Akesson (1975) report measuring between 0.14 and 10 grams per hectare 1000 meters downwind from an agricultural spray using high volume air sampling equipment. Unless a need for more sensitive detection can be shown, a lower limit of 10^{-8} gram per square centimeter total vertical flux should be realistic for our objective.

SUMMARY

In an attempt to find a standard sampler for measuring coarse aerosol carried off target by surface winds, MEDC recommends the following:

1. Assume a nearly instantaneous line source.

2. Use total flux as primary reporting standard for drift.

3. Establish minimum detection level not less than 10^{-8} gram per square centimeter.

4. Sample for droplets from 15 to 50 μm.

We are soliciting comments on our recommendations from individuals responsible for conducting spray projects or assessing impact of drift. We are particularly concerned with: (a) purpose and priority of drift sampling; (b) criteria for evaluating samplers; (c) standards for reporting; (d) sampling size range and detection levels.

Comments will be summarized by MEDC. A group of representatives from both the National Forest system and Research, who are experienced in aerial application and environmental impacts, will be selected to review and recommend for approval the reporting standard and criteria for drift monitoring. MEDC will use these reporting standards and drift sampling criteria to develop a standard sampler for detecting and measuring coarse aerosol.

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Appendix E

Interfacing the Forest Service Spray Dispersal Models
AGDISP and FSCBG
To a Complex Terrain Model

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Recently, the USDA Forest Service initiated a study examining the extension of the spray dispersal models AGDISP and FSCBG into complex terrain. This note discusses the issues that may be important when interfacing the two existing models with a complex terrain model.

There are a wide variety of computer models that address complex terrain; their advantages and disadvantages have been discussed elsewhere (Lewellen and Sykes, Ref. 1). AGDISP (Bilanin, et al., Ref. 2) and FSCBG (Rafferty and Bowers, Ref. 3) are spray dispersal prediction models restricted to flat terrain. It would seem natural to suggest that the appropriate models (or concepts) be merged to provide a more general purpose model that would be capable of solving a larger class of problems.

For the purpose of this note, it makes sense to suggest the following spray scenario. In the early morning hours a spray application occurs upvalley. Material that does not deposit on the canopy or the ground is kept aloft (either by the aircraft vortex wake, evaporation or small drop size) and will drift down the valley under the influence of the dominant valley circulation. As the sun rises, differential heating will destroy the thermal inversion and affect the fate of this airborne material. Material that drifts aloft and rises above the valley crest will be uncontrolled and its eventual destination can only be speculated upon. Material that travels down the valley will eventually deposit within the observation grid. Although the valley may have sidewalls, it is probably a good first assumption that the valley downslope is less than five degrees. Given the reality of data collection, it is also probable that only one meteorological station (on the valley floor at the spray area) will provide atmospheric data.

AGDISP and FSCBG require a specific set of inputs, including:

Meteorology -- temperature, relative humidity, wind speed, wind direction;
Aircraft -- weight, wing span, engine details, release height, flight paths;
Nozzles -- location, type, flow rate;
Spray Material -- drop size distribution, volatile fraction; and
Canopy -- height, shape, structure.

All of these inputs define the conditions at the spray area, with or without the presence of complex terrain. Note that the terrain effect is a longer time scale than the spray mission effect. For a first approximation it is probably valid to assume that the spray mission occurs instantly with respect to downvalley behavior.

Both models assume a flat terrain. Again, this is probably a good assumption since the local geometry at the spray area will be nearly level. If distinct terrain is present in the cross-flight direction, the image vortices (in AGDISP) and image Gaussian plumes (in FSCBG) could be modified to account for it.

The output options in AGDISP and FSCBG could be configured to include the generation of specific data files to be used subsequently in a complex terrain model. In this way the integrity of both models is preserved, for the many times when terrain is not an issue or is an effect of little importance.

Much effort has gone into running both spray models on the personal computer and in the Data General environment. Most users of the models expect results in 10 to 30 minutes. A complex terrain model at the back end probably cannot run longer than 30 minutes without the user base abandoning it.

Both models are now amenable to hand off to a complex terrain model. My suspicion is that a puff or plume model would be used (to save computer time), and the necessary input information could be generated from either AGDISP or FSCBG. FSCBG is, however, more amenable to this approach because it already solves AGDISP in the near-wake, hands off to the Gaussian line sources for the far-wake, and solves for deposition. Concentration models would be needed in AGDISP and are already present in FSCBG (but not validated). These concentration models would generate the plume characteristics needed for input to a complex terrain model.

The present AGDISP and FSCBG models would have to be modified to include the effects of stratification. In the near wake, stratification would modify the behavior and persistence of the aircraft vortices (Hecht, et al., Ref. 4), require the evaporation model in AGDISP to be improved to include temperature and pressure effects (Teske and Bilanin, Ref. 5), and generalize the image vortex structure below the surface (to maintain the no-flow boundary condition). In the far wake, the meteorological model would require reexamination. The concentration of material aloft would have to be interpreted into (possibly) multiple volume sources for input into a complex terrain model. The spray application should be well predicted by the assumptions of locally horizontal terrain and short duration (30 minutes or less) before sunlight enters the spray area.

Both models currently have extensive graphics; additional graphics would be needed to provide visualization of the input to the complex terrain model. The complex terrain model should also have extensive graphics in keeping with the level of commitment to graphics in AGDISP and FSCBG. Users are not used to looking at columns of numbers.

Clearly, a complex terrain model should be decided upon, then its interaction with AGDISP and FSCBG determined. Concurrently, concentration predictions could be programmed into AGDISP, and stability into both models, along with graphics to visualize the three-dimensional spray plume.

In summary, it is recommended that the Forest Service define the parameters of the complex terrain problem desired to keep the model development as simple as possible. A cursory examination of complex terrain models suggests that there is no model that is easily adapted to the proposed spray scenario envisioned for the Forest Service. All of the numerical techniques needed to expand the present models (AGDISP and FSCBG) are in hand. Computer programs would not have to be developed from scratch. Validation of AGDISP and FSCBG should continue without regard to the complex terrain issue; however, validation of the complex terrain model would undoubtedly be necessary. It is hoped that resource people (R. N. Meroney, C. D. Whiteman, and perhaps J. F. Bowers of Dugway Proving Ground) would be retained to review the selection, enhancement and validation of the complex terrain model eventually developed in this effort. Once a complex terrain scenario is understood, programmed, reported and accepted, then extensions to more difficult terrain issues, and pretty pictures, could be suggested. For now it makes

sense to keep things as simple as possible to control not only the understanding of complex terrain, but also the funds needed to pursue this effort.

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Reply To: 2150

Date: June 5, 1990

Subject: Technology Projects

To: Bob Ekblad
Missoula Technology Development Center

As you know the Technology Project Task Force will meet at Ft. Collins, CO, in August to review progress of the FY90 projects and proposals for FY91. A work plan was to be submitted by each funded researcher and a project status report is due to the committee by August 3, 1990. I believe you have Jim Space's letter of May 4, 1990 regarding the meeting.

MTDC and this office were funded for two projects <u>Droplet Evaporation Model</u> and <u>Complex Terrain Model</u> with you as project leader for both projects. I realize that project approval and funding were late in arriving, thus you have not had adequate time to develop these projects. Pressing at the moment, however, is need for work plans that detail your approach, expected accomplishments, and funding needs for FY91 and possibly beyond. These plans should be reviewed in draft form by WO/FPM, selected cooperators, and the Spray Model Advisory Committee. Consistent with our mutual technology transfer program we need to involve users at all levels throughout all product development. FPM has assigned evaporation as the highest priority of the two projects. Below are a few summary comments and thoughts I have on these two projects.

<u>Evaporation</u>

Recognizing that drop evaporation is one of the most important factors affecting deposition and drift, measuring and predicting evaporation is a high priority. To summarize AGDISP and FSCBG have within their construct codes for predicting evaporation. AGDISP has a relative simple code while FSCBG has a theoretical and a complex code in addition to its simple equation for evaporation of water. The complex part of the code can predict evaporation given several physical property inputs as follows:

Molecular weight
Diffusivity
Latent heat of vaporization
Molar vapor density
Ambient vapor pressure
Vapor pressure coefficient B
Vapor pressure coefficient C
Thermal cond. of vapor

The Droplet Evaporation Model project was to look at existing codes that might predict evaporation of multi-component tank mixes. As you know we have not been successful in obtaining these measurements for single component tank mixes much less multi-component ones. Consequently we have not used this more complex method of predicting evaporation. Noting that the code came from the U.S.Army I asked them who might be able to obtain these measurements and they could not provide an answer. I also asked this question of pesticide manufacturers and met the same response. Apparently these measurements are done only by certain specialized laboratories. I also brought this up before the NACA Technical Committee and there was no support indicated. If we wanted to pursue this we could advertise for someone to make these measurements but we would have the problem of quality control and costs. Therefore I believe this theoretical approach to evaporation is impractical for our purposes and that we should not pursue it further. An alternative, as we discussed and recommended to NACA, is to measure evaporation of selected tank mixes in the laboratory or wind tunnel, develop an equation for each tank mix, and use it directly in the model.

This of course is what you had contracted Colorado State University (CSU) to do for us several years ago. I would like for you, under the evaporation project, to compare the CSU evaporation study results to AGDISP and FSCBG predictions and look a goodness of fit. This would give us some ball park idea of how well the models are predicting evaporation. We had talked about doing something like this with Milt Teske about a year ago and the need to recreate some of the model inputs. What all this adds up to is revising the plan from your original intent and moving forward.

Complex Terrain Modeling

FPM considers need for a complex terrain model secondary to the matter of evaporation. This project, however, is far more complex and will take much more time and evaluation to complete. Project scope includes predicting diffusion and movement of particulates and their volatile fractions, over forests in undulating and mountainous terrain. An existing complex terrain model, to be connected to the initial source distribution from the FSCBG model, would be supported by a geographical information system. The combined model system would be supported by state-of-the-art, three dimensional plotting programs and hardware. We need to establish contacts with EPA on visualization as mentioned in my EPA trip report. FPM is primarily interested in deposition as opposed to air concentration. Deposition from a practical viewpoint is a short distance phenomena and our field people tell us they need to know how far there will be detectable deposits of drift. No FS person has ever asked me how far downwind the material is detectable in the air, although some ask where is the unaccountable 70% of the spray. One of the reasons the U.S.Army developed FSCBG was to predict air concentration of the study agents. The FS needs this information for human risk assessment primarily for chemicals. And of course we apply few chemicals these days. So this is the rational for assigning a lower priority complex terrain. The agricultural community should be keen on the air concentration problem and they should pay for the work. I would like also appreciate your thoughts on "total" spray accountancy in the event we need to take a serious approach this problem. My definition of total is accounting for 90% of the tank mix. From the complex terrain aspect I am interested in

drift deposition in the near field up to 1 mile and predicting plume movement downwind no more than 10 miles or until up-slope wind develop.

This about covers a few thoughts. Please call if you wish to discuss.

/s/ John W. Barry

John W. Barry
Program Manager

PROJECTS FOR CONSIDERATION FOR SPECIAL FUNDING FOR FY 1990

Submitted by Robert Ekblad
Missoula Technology and Development Center

PROJECT TITLE: Selection and verification of a Complex Terrain-Wind Flow Model for Spray Transport.

FY 1990 $80,000
FY 1991 25,000

Note 1. This project has already been submitted for consideration for special project funding.

PROJECT TITLE: Selection and Verification of Spray Droplet Evaporation Model.

FY 1990 $74,900
FY 1991 0

Note 2. This project has already been submitted for consideration for special project funding.

PROJECT TITLE: Additions and Enhancements to AGDISP.

FY 1990 $65,460
FY 1991 70,760

Note 3. The funding requested for FY 1990 is for new capabilities and minor housekeeping. The FY 1991 funding is more for user-friendly and easier operation features.

PROJECT TITLE: Selection and Verification of a Complex Terrain-Wind Flow Model for Spray Transport.

PURPOSE: To select an existing complex terrain-wind flow model and incorprorate it into the AGDISP and FSCBG aerial spray models.

BACKGROUND/JUSTIFICATION: Wind movements near the earth surface are channeled and directed by irregular topographic features, temperature structures, strength of overlying winds,etc. These winds and thir intensities determine the direction and ultimate fate of off site spray movement and where it will deposit. The AGDISP and FSCBG models do not account for irregular topographic features.
Models to describe wind movement over complex terrain have been developed by the Forest Service, U S Army, EPA, and others for specialized applications. The models are applied by meteorology specialists and are not accessible for routine use by spray specialists. The models are programmed on computers and depend on the existence of digital terrain descriptions. The models that are available range from simple site specific regulatory models to sophisticated full physics numerical models that require supercomputers, such as a Cray. The challenge is to select a model that is accurate enough to be useful and is compatible with the software and computers used for our current aerial spray models.

METHODS: We plan to conduct a workshop to review the Forest Service model requirements and to recommend likely candidate models. We will establish selection criteria based on input requirements, computational time, scientific correctness and other parameters. We expect to screen DIAGNOSTIC FLOW, POTENTIAL FLOW, THERMAL FLOW and FULL PHYSICS NUMERICAL MODELS. The most promising models will be obtained and installed on a suitable computer. The results of benchmarking and comparison of the models will be presented in report for review by the steering committee. The model that is finally selected will be incorporated into the AGDISPand FSCBG models.

PRODUCT: Products will consist of an interim report after the first workshop, an interim report recommending models for screening on the computer, and a report documenting the final selection. The final product will be a revised version of AGDISP and FSCBG, complete with documentation.

COST AND BENIFITS: The total project cost is $120,000 over a one year period, with $105,000 requested from special project funding. The economic benefits will result from improved predictions of spray behavior, that will lead to better control and improved predictions of off site movement of pesticides. This will reduce side-effects and improve our credibility with the public.

COOPERATORS: MTDC (Missoula Technology and Development Center R.Ekblad) will have lead responsibility for contracting, model selection and overall coordination. WO/FPM (J. Barry) will be responsible for defining model deposition requirements. Battelle, Pacific Northwest Labs (Dr D. Whiteman) will be responsible for conducting workshops and selecting models for review and computer evaluation. A University or private contractor will be responsible for installing and running the selected models on a computer. Continuum Dynamics (Dr M. Teske) will be responsible for incorporating the wind flow models into the AGDISP and AFSCBG models.

BUDGET: (pm denotes person-months)

FY 1990

	Total Cost	Covered Costs	Requested Funding
MTDC:			
Engineer (3pm)	$15,000	$15,000	$ 0
Publications (2pm)	10,000	0	10,000
Travel	4,000	0	4,000
Battelle, PNW:			
Interagency Agreement	34,000	0	34,000
Continuum Dynamics, Inc:			
Contract	25,000	0	25,000
University or Private Firm:			
Contract	20,000	0	20,000
Steering Committee			
Travel	12,000	0	12,000
TOTAL	120,000	15,000	105,000

TOTAL AMOUNT REQUESTED FROM FPM SPECIAL PROJECTS 105,000

PROJECT TITLE: Selection and Verification of Spray Droplet Evaporation Model

PURPOSE: To develop an improved model that can be incorporated into the FSCBG, AGDISP or any other spray model to predict changes in droplet size and concentration due to evaporation.

BACKGROUND/JUSTIFICATION: A critical factor in the aerial spray predictions models is the evaporation rate associate with the spray droplets. Evaporation affects the droplet size and hence the terminal velocity of the drop. Consequently, evaporation has significant impact on the time and space distribution of the spray. A study by Dr Banaugh, in 1979, revealed that most of the theoretical research was done for pure liquid drops. In order to have information for the spray models, a study was sponsored at Colorado State University to measure evaporation rate of droplets from 13 pesticide mixtures under simulated free fall conditions. No further use was made of the windtunnel and it was removed and dismantled. Both the AGDISP and FSCBG are confiqured to accept data from the simulated tests or to calculate evaporation rate for pure liquids when certain physical properties are known.

This year a new study was sponsored to review and update the status of droplet evaporation research and development. Eight organizations have been identified that have done recent testing of droplet evaporation. The U S Army, CRDEC, at Aberdeen Proving Ground has developed the most complete and thorough evaporation model for multi-component mixtures, including emulsions and suspensions. NUSSE4 (the CRDEC model) can simulate up to five components. The five components can include two volatile and three non-volatile components. Only limited validation of the model predictions havce been made to date.

Since the pesticide tank mixes have changed, we no longer have valid experimental results for the spray model, nor do have multi-component models operational.

METHODS: We plan to obtain the NUSSE3 and NUSSE4 models and maker them operational on a Forest Service computer. We will determine the physical constants needed to exercise the model and obtain those constants from the pesticide manufacturers if possible. We plan to obtain experimental measurements of new tank mixes and compare those results to the model predictions. Comparisons of previous experimental results will made to existing models. Revisions to the model will be proposed based on comparisons to experimental measurements.

PRODUCT: Products will consist of a FORTRAN computer code for droplet evaporation, documentation for the code and a MTDC Project Record detailing methods, resuslts and conclusions.

COST AND BENEFITS: The total project cost is $84,900 over a one year period, with $74,900 requested from special project funding. The economic benefits will result from improved predictions of spray deposit, that will lead to better control and improved predictions of off site movement of pesticides that will reduce side-effects and improve our credibility with the public.

COOPERATORS: MTDC (R. Ekblad) will have the lead responsiblity for engineering, modeling, technical accuracy and overall coordination. WO/FPM (J. Barry) wil be responsible for selecting tank mixes and coordination with pesticide manufactureres. Army, CRDEC (A.Stuemple, E. Penski and R. Pennsyle) will provide the model(s) and assistance in operating them. Experimental results will be provided by one of eight organizations indentified as having that capability. CDI (M. Teske) will provide assistance in programming and identification of evaporation modules within both AGDISP and FSCBG.

BUDGET: (pm denotes person-months)

FY 1990

	Total Cost	Covered Cost	Requested Funding
MTDC			
Engineer (2pm)	$10000	$10000	$0
Programmer (1pm)	5000	0	5000
Publications (1pm)	5000	0	5000
Travel	4500	0	4500
Army (CRDEC)			
Interagency Agreement	10000	0	10000
CDI			
Contract	10000	0	10000
Other Organization			
Contract	40000	0	40000
TOTAL	84900	10000	74900
TOTAL AMOUNT REQUESTED FROM FPM SPECIAL PROJECTS			74900

R.Ekblad 8/4/89